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Baseline choice and performance implications for REDD

Pana, Anca Claudia ; Gheyssens, Jonathan

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DOI: https://doi.org/10.1080/21606544.2015.1028465

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Journal Article
Accepted Version

Originally published at:
Pana, Anca Claudia; Gheyssens, Jonathan (2016). Baseline choice and performance implications for REDD. Journal of Environmental Economics and Policy, 5(1):79-124.
DOI: https://doi.org/10.1080/21606544.2015.1028465

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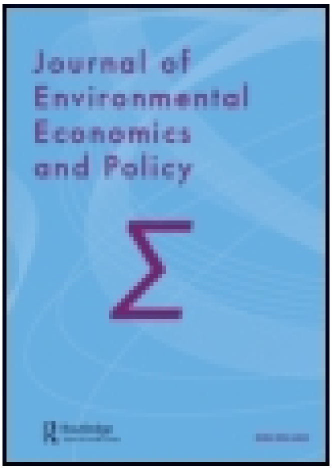

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Journal of Environmental Economics and Policy

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/teep20

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Anca Claudia Pana[a] & Jonathan Gheyssens[b]

[a] Institute for Banking and Finance, University of Zurich, Plattenstrasse 32, 8032 Zurich, Switzerland

[b] REDD+ Finance and Sustainable Land Use, UNEP Finance Initiative, International Environment House, 11-15 Chemin des Anmones, CH-1219 Chtelaine, Geneva, Switzerland

Published online: 13 Apr 2015.

To cite this article: Anca Claudia Pana & Jonathan Gheyssens (2015): Baseline choice and performance implications for REDD, Journal of Environmental Economics and Policy, DOI: 10.1080/21606544.2015.1028465

To link to this article: http://dx.doi.org/10.1080/21606544.2015.1028465

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Journal of Environmental Economics and Policy, 2015
http://dx.doi.org/10.1080/21606544.2015.1028465

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Baseline choice and performance implications for REDD

Anca Claudia Pana[a]* and Jonathan Gheyssens[b]

[a]*Institute for Banking and Finance, University of Zurich, Plattenstrasse 32, 8032 Zurich, Switzerland;* [b]*REDD+ Finance and Sustainable Land Use, UNEP Finance Initiative, International Environment House, 11-15 Chemin des Anmones, CH-1219 Chtelaine, Geneva, Switzerland*

(*Received 8 May 2014; accepted 9 March 2015*)

Reducing Emissions from Deforestation and forest Degradation (REDD) projects are being designed and implemented across tropical countries, intending to curb the contribution of deforestation to greenhouse gas emissions. An important aspect of REDD implementation is the *baseline* against which reductions are measured. The baseline estimates the business-as-usual emissions from deforestation and forest degradation. We solve a dynamic model of land conversion from forest to agriculture in the presence of REDD, and assess the performance of four baselines. We show that none of the analysed baselines dominates in all performance aspects, and that the final baseline choice needs to maximise the trade-off between the effectiveness to reduce deforestation, cost-efficiency, and changes in income. The frequently used historical average baseline could be improved by using a forward-looking one, which is shown to better account for the opportunity costs faced by landowners. This result hinges on the ability of the baseline to predict deforestation rates without significant underestimations. We advocate the switch from a single-threshold baseline to a corridor methodology, which would provide continued incentives to reduce deforestation, even during periods of high opportunity costs. We finally show how the selection of certain baseline attributes, such as corridor bandwidth and symmetry, can enhance performance.

Keywords: deforestation; REDD; baselines; effectiveness and efficiency

1. Introduction

Emissions from deforestation and forest degradation rank as the second largest source of carbon dioxide in the atmosphere after fossil fuel combustion, contributing about 12% of global anthropogenic emissions (van der Werf et al. 2009). Programmes targeting the Reduction of Emissions from Deforestation and forest Degradation (REDD and REDD+)[1] have emerged as potential instruments for stabilising atmospheric CO_2 concentrations and mitigating climate change.

REDD programmes target forest preservation in tropical areas, where deforestation is the largest contributor to total greenhouse gas (GHG) emissions (van der Werf et al. 2009). Here, the major drivers of deforestation have often been identified as timbering, land conversion to agriculture, cattle ranching, and the establishment of new settlements (Pfaff et al. 2013). Restricting deforestation would limit the development of such land-use activities and alter the revenue flow of landowners. To compensate for the foregone income from deforestation, REDD schemes offer financial rewards for forest conservation.

*Corresponding author. Email: anca.pana@bf.uzh.ch

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REDD programmes aim to achieve *additionality*, i.e. payments are intended to reward reductions in emissions from deforestation below business-as-usual (BaU) levels. However, the counterfactual deforestation rates and the corresponding emissions, which would occur in the absence of the policy, are not observable and, therefore, highly challenging to assess. Thus, REDD payments are linked to reductions below estimations of the BaU levels, called *baselines* or *reference levels*.

The reward system of REDD can be financed through the creation of special funds or be designed as a market mechanism (Palmer 2010; Corbera and Schroeder 2011). In the second case, reducing emissions from deforestation below a reference level generates credits eligible for sale on various carbon markets. International emitters[2] that are above their compliance level and short of CO_2 permits might find reducing emissions internally to be expensive (Diaz et al. 2011) and could benefit from the comparative affordability of REDD permits (Kindermann et al. 2008; Stern 2008). Despite this economic advantage, REDD projects remain complex to implement and prone to failure. Various aspects appear problematic: the measurement of reductions in emissions below BaU levels; raising sufficient funds for implementation or establishing a link with (immature) carbon markets; the risk that forest loss will be postponed in time (lack of permanence) or transferred to unregulated areas (leakage); and the existence of clear property rights that would rule out false permit claims from encroachers (Angelsen 2008a).

The success of REDD is critically sensitive to the incentive structure promoted by the schemes (Griscom et al. 2009; Cattaneo et al. 2010; Busch et al. 2012). A central aspect is the establishment of the baseline against which reductions in emissions from deforestation are measured and financial rewards are granted. However, setting the baseline is not a straightforward task. First of all, to encourage participation and ensure significant reductions in GHG emissions, the baseline design would need to ensure that REDD rewards cover the various opportunity costs of deforestation (Irawan et al. 2013). At the same time, the selected baseline should achieve emission reductions in a cost-efficient manner, avoiding that payments greatly exceed opportunity costs and result in windfall profits for landowners (Busch et al. 2012), instead of being used for reducing deforestation elsewhere. As well, flooding the carbon markets with REDD credits in large supply would drive the CO_2 permit price down and possibly reduce the effectiveness of the carbon markets (Doupé 2014).

Several organisations have emerged with the goal of assisting countries in participating successfully in REDD programmes, by offering technical, legal, and financial support. Among them, notable actors are the Forest Carbon Partnership Facility, the Amazon Fund, the UN-REDD programme, Norway's International Climate and Forest Initiative (NICFI), and the German REDD Early Movers Program. So far, the existing REDD initiatives supported by these organisations have endorsed the decision of the UNFCCC to compute reference levels based on past deforestation rates, adjusted to account for country circumstances[3] (UNFCCC 2009, Decision 4/CP.15). The decision to opt for historical reference levels is motivated by the desire to ensure transparency and credibility (The German REDD Early Movers Program 2014). In order to account for national circumstances, historical averages can be adjusted upwards for countries with historically low deforestation rates and high remaining forest areas; downward adjustments are allowed for countries with clear decreasing trends in deforestation (FCPF Carbon Fund 2013).

Despite its recognised advantages, the historical baseline lacks the ability to reflect future drivers of deforestation. Moreover, provided as an average, it neglects the variability observed in deforestation rates, coming from fluctuating economic conditions. The historical baseline might, therefore, fail to account properly for the true opportunity costs

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that landowners face. Trying to address these issues, several baseline methodologies have been proposed; for an overview, see Huettner et al. (2009) and Griscom et al. (2009). Our paper attempts to provide further insights into how to choose the most robust and effective baseline methodology.

This paper joins the literature dedicated to the optimal contract design of REDD schemes (Huettner et al. 2009; Busch et al. 2009, 2011; Sathaye et al. 2011). We compare the impacts of four different baselines on REDD success. We focus on two of the most popular baseline categories: a retrospective baseline reflecting the historical average deforestation and a model-implied prospective baseline that proxies the BaU deforestation path in the absence of the REDD programme. We also analyse the so-called *fixed-corridor* approach, which replaces the historical threshold with a lower and an upper bound below and above the historical deforestation average (Schlamadinger et al. 2005). Additionally, we propose a new baseline type, the variable-corridor approach, which aims to gather the strong points of the model-implied and the corridor baselines.

Our analysis proceeds as follows. First, we show how to model land-use decisions in the presence of REDD in a dynamic setting. Second, we rank baselines according to different performance indicators: (1) a measure of forest preservation (effectiveness), (2) an indicator of the cost of this preservation per hectare (efficiency), and (3) a measure of changes in the total income of the landowner (change in welfare). In particular, we check what are the losses in effectiveness when the BaU deforestation path is estimated with error, impacting the REDD payments. The economic analysis is further put into perspective through a qualitative evaluation, accounting for environmental, technical, and social concerns with REDD. Finally, the paper explores different possibilities to improve the performance of the corridor baselines, by varying corridor width and symmetry.

Previous research on REDD design overlooked the inter-temporality dimension in forest decisions (Huettner et al. 2009; Busch et al. 2009, 2011). Huettner et al. (2009) ran a survey to qualitatively compare three types of retrospective baselines, based on the historical deforestation rate, with a forward-looking baseline. We extend the types of baselines analysed beyond those considered in Huettner et al. (2009) and focus on the economic incentives generated by each baseline. Busch et al. (2009) approach the ranking of different baselines via a one-period partial equilibrium model at the country level. They show that an effective national baseline simultaneously provides incentives to reduce deforestation in areas of high rates and ensures the continuation with low deforestation practices in areas of low previous forest loss. Busch et al. (2011) extend this approach by introducing different levels of annual REDD financing, either through funds or through access to a dedicated market. They highlight the importance of designing baselines that minimise leakage to unregulated areas and are generous enough to guarantee the participation of both countries with high or low deforestation rates. Cattaneo et al. (2010) use a static partial equilibrium model to compare five different baseline designs from an equity perspective. They show that the crediting schemes considered obtain similar reductions in deforestation, but differ greatly in terms of cost-efficiency and two measures of equity.

The highly dynamic nature of land-use practices has been studied in numerous papers and benefits from a large variety of models; for a review, see Verburg et al. (2004). However, only a few papers deal explicitly with dynamic land-use change in the presence of REDD (Ollivier 2012; Lu and Liu 2013; Vitel et al. 2013; Mosnier et al. 2014), and none of them tests for different baseline methodologies. We attempt to fill this gap by analysing our selected baselines with a dynamic land-use model. The dynamic model helps us illustrate the optimal deforestation decisions at several points in time, and show how landowners choose to take part in REDD depending on the time-varying opportunity costs for deforestation. Anticipating our results, with the help of the dynamic approach we are able to demonstrate that some baseline methodologies offer continued incentives to keep deforestation below BaU levels, while others achieve only temporary effectiveness. This finding is key to understanding how we could potentially solve non-permanence issues with REDD and can only be grasped in a dynamic setting.

Another important decision concerning REDD implementation is the choice of the administrative level at which emission reductions are calculated and payments are made. While the accounting of emission reductions and the management of REDD payments is most likely to take place at the national level, land-use decisions are usually taken at the subnational (regional or household) level. This reinforces the need to understand the incentives received by the local landowners (Angelsen 2010; Busch et al. 2012). Our model describes the decisions of a single landowner who optimises over the rate of deforestation as he or she expands agriculture activities. The single-agent approach is in line with the literature on optimal forest extraction (Angelsen 2007) and with a new literature trend arguing that REDD will face the same issues as traditional integrated conservation and development projects, since it will have to account for incentives at the community and individual levels (Blom et al. 2010). It is not intended to suggest that the complexity of implementing REDD projects can be summarised into a single-player model; nonetheless, we believe that our approach is relevant for highlighting the behavioural changes at the micro level, which can then be used to inform national or jurisdictional policy decisions.

The choice of the administrative level for REDD is expected to impact the effectiveness in reducing deforestation. Implementing REDD at the site level, and then aggregating results at a larger (national) scale, may give way to leakage of deforestation to other areas (Busch et al. 2012), and raises questions regarding the organisation of carbon payments at the local level.[4] However, the estimation of reference levels is more likely to reflect the BaU deforestation path if set at the household level, since jurisdictions at lower scales may have better information regarding the specific drivers of deforestation in the area (Busch et al. 2012). Potential policies for avoiding leakage include (1) the monitoring of deforestation rates at the national level and (2) the setting of penalties for deforestation rates that exceed the estimated BaU level, coming from beneficiaries of REDD payments elsewhere. In this paper, we adopt the view that REDD should focus on providing incentives for reduced deforestation at the local level, while ensuring national monitoring.

Our analysis reaches several conclusions that we hold relevant for the design of forest carbon policies. First, solving for the optimal deforestation rate under a REDD regime, we show that the baseline choice impacts REDD performance at multiple economic, social, and environmental levels. None of the considered baselines can fulfil all REDD criteria simultaneously, and the baseline choice needs to maximise the trade-off between the different goals. We argue that the widespread current practice of rewarding emissions below the historical deforestation average could be improved by implementing a forward-looking baseline that would better account for the opportunity costs faced by landowners and would result in higher emission reductions. This result depends, however, on the ability of the forward-looking baseline to predict future deforestation rates without substantial underestimations. Finally, we advocate the switch from a single-threshold baseline approach to a corridor methodology; this reduces losses from estimation errors and provides continued incentives for reduced deforestation, even during periods of high opportunity costs.

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The rest of the paper is organised as follows. Section 2 introduces our methodology and the main assumptions of the dynamic model. In Section 3, a numerical application is performed and the robustness of our results is tested. Section 4 concludes on the policy implications of our results and the link with broader issues of REDD implementation.

2. Methodology

2.1. Model setting

In our model, the owner of a large area of forested land decides if, when, and to what extent to exploit the forest for agricultural activities. To limit his or her deforestation, the owner is offered the possibility to take part in a REDD programme that grants carbon permits each time the deforestation rate is below a pre-specified threshold. We model the voluntary participation in REDD along the approach of Busch et al. (2009, 2011), where the owner can 'opt in' as long as he or she considers this to his or her advantage.[5] In our model, reforestation options are not accounted for; this assumes that costs for switching back from cropland to forest (together with the forgone discounted cash flows from agriculture) are large enough to render the reforestation option unattractive.

The landowner's revenues are a trade-off between the net income from land exploitation and REDD rewards. The more the owner deforests, the higher the incomes from selling timber and subsequently using land for agricultural activities, and the lower the number of received REDD permits. Alternatively, lower deforestation (below the defined baseline level) results in smaller incomes from agriculture and timbering, but higher REDD revenues. We choose an approach similar to Busch et al. (2009), where the owner's revenues from land exploitation are modelled as a unique composite commodity, representing both the harvesting value of timber and a perpetual discounted flow of agricultural activities on the land.[6]

The owner maximises the sum of total discounted profits, taking into account the parameters that define the decision environment: the state of the forest, the dynamics of composite commodity and REDD permit prices, and the specified deforestation baseline. In our model, the prices of the composite commodity ($P^{cc}(t)$) and of the REDD permit ($P^{R}(t)$) are exogenous and follow deterministic dynamics[7]:

$$dP^{cc}(t) = \delta P^{cc}(t)dt \tag{1}$$

$$dP^{R}(t) = \gamma P^{R}(t)dt \tag{2}$$

where δ and γ represent the respective growth rates of the two price processes. Being a composite price, $P^{cc}(t)$ is a simplification of the actual commodity flow generated from harvesting one hectare of forest and using the area for perpetual agricultural activities, which could be modelled as follows:

$$P^{cc}(t) = P_h(t) + \int_t^{\infty} A(t)e^{-\psi t}dt \tag{3}$$

where $P_h(t)$ represents the one-time timber harvest selling price, while $A(t)$ are the annual monetary flows from agricultural activities after land conversion. Land exploitation involves various operational costs that we model with the help of a quadratic function:

$$C(t) = a_1 d(t) + a_2 d(t)^2 \tag{4}$$

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where $d(t)$ is the amount of forest converted to agriculture at time t. We assume the parameters of the cost function (a_1, a_2) to be constant. This stylised representation is in line with the classical approach of von Thünen (1826): when land is abundant and homogeneous, the agriculture expansion frontier depends on the cost of accessing new forest patches, which are farther away from the initial location and thus costlier to exploit (Angelsen 1999).

The offsetting scheme proposed by REDD imposes no liability: the owner is rewarded if the deforestation is below a certain reference level, but does not have to pay penalties in case this limit is exceeded (Griscom et al. 2009; Huettner et al. 2009; Joanneum Research Institute 2006). The owner's revenues from REDD ($RR(t)$) can be described by a step function:

$$RR(t) = P^R(t)(dB - d(t))^+ \tag{5}$$

where $P^R(t)$ is the REDD permit price at time t, dB the baseline level, and $d(t)$ the actual deforestation at t. REDD cash flows are zero for deforestation rates above the baseline, i.e. $(dB - d(t))^+ = 0$ if $d(t) \geq dB$. REDD programmes define reference levels (dB) in terms of tonnes of CO_2 equivalent per year. To simplify the presentation of results, we convert reference levels into hectares of avoided deforestation, as described in Section 2.3. Unlike in the traditional dynamic setting, we introduce a loose constraint on the total owned patch of forest at $t(0)$ $\left(\overline{F}(0)\right)$. However, we impose a time window $[0, T]$ during which the optimisation occurs. While $\overline{F}(0)$ is not infinite, we consider its value so large that forest depletion is not likely[8]; we allow for a positive terminal stock at period T. However, future REDD schemes may have an explicit time frame[9] (Parker et al. 2008), which compels us to consider the time constraint as the most binding for the landowner.

We first solve the model for the BaU case (the benchmark when no REDD project is in place), and then for four REDD crediting baselines: historical, model implied, and two types of corridor. We proceed now with the presentation of each scenario, and then assess the incentives for avoiding deforestation observed in each case.

2.2. *Baseline alternatives*

2.2.1. *Business-as-usual scenario (without REDD)*

The BaU scenario illustrates the deforestation trend in the absence of REDD or other forest conservation projects. Here, the land brings only timbering and agriculture benefits, as reflected in the net cash flow ($\pi(\cdot)$) at time t:

$$\pi(d(t)) = P^{cc}(t)d(t) - (a_1 d(t) + a_2 d(t)^2) \tag{6}$$

where $P^{cc}(t)$ is the composite commodity price, $d(t)$ the deforestation rate, and a_1 and a_2 are the parameters of the cost function. The optimal control problem can be described as a maximisation over the deforestation rate of the total discounted net revenues resulting from land exploitation:

$$\max_{(d(t))_{t\in[0,T]}} \left\{ \int_0^T e^{-rt} \pi(d(t)) dt \right\} \tag{7}$$

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where r is the discount rate and T marks the end of the decision horizon. The variation in the stock of forested land is given by the following dynamics:

$$\dot{F} = -d(t) \tag{8}$$

where F is the stock of forest and $\dot{F}$ represents its variation between consecutive periods. We follow the solution approach of Chiang (1992) for determining the optimal deforestation path (see the Appendix). The rate of deforestation at each moment of time is recursively linked to the initial deforestation level:

$$d(t) = d(0)e^{rt} + \frac{P^{cc}(0)(e^{\delta t} - e^{rt}) - a_1(1 - e^{rt})}{2a_2} \tag{9}$$

Reflecting the optimal deforestation path in the BaU scenario, we denote $d(t) = d_{\mathrm{BaU}}(t)$; it will be used below for computing the REDD rewards in the model-implied and the variable-corridor scenarios.

2.2.2. Historical baseline

Most proposals include the historical average deforestation rate in the computation of the crediting baseline[10]; this comes as a recognition of the fact that the average past deforestation, although an imperfect measure, is one of the best predictors at hand for short- to medium-term deforestation (Angelsen et al. 2009). We thus start the analysis of the deforestation behaviour under REDD with a simple historical baseline, where the REDD threshold is flat and equal to the average past deforestation rate. This baseline type is a simplification of what has been proposed by Brazil (Parker et al. 2008).

The merit of the historical baseline consists of its fair simplicity of computation and implementation, as well as its appeal to countries and landowners who need to get used to new operation rules. The baseline has received support also for its ability to reflect local deforestation trends.

The historical reference level faces, however, a number of limitations. Most importantly, an imperfect predictor of future deforestation has high chances of undermining the additionality principle and of distorting country participation, especially if one considers the specific forest transition stage[11] of each country (Angelsen 2007). Forest-rich states with low past deforestation, but which expect increasing trends, might decide to stay out of REDD if the programmes are based on historical baselines. On the other hand, nations with large past deforestation rates and scarce remaining forests would gladly join, since rewards based on historical averages would be generous relative to the required additional efforts (Angelsen 2008a).

In the presence of REDD with a historical baseline, cash flows are generated by two counter-balancing activities, i.e. forest exploitation and REDD:

$$\pi(d(t)) = P^{cc}(t)d(t) - (a_1 d(t) + a_2 d(t)^2) + P^R(t)(dB - d(t))^+ \tag{10}$$

As captured in Equation (10), the landowner's profits are determined by the sales of the composite commodity, less the operational costs; additionally, REDD revenues are eligible for deforestation rates below the historical threshold (dB).

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2.2.3. Model-implied baseline

An alternative to the retrospective historical baseline is the prospective method[12] that incorporates projections of future deforestation trends. The *model-implied* baseline relies on a time-varying level reflecting predicted deforestation paths under the BaU scenario. Here, the landowner is rewarded for deforesting less than in the absence of the REDD programme. If the forecasting is accurate, it enforces additionality, since only actual efforts would be rewarded. However, the model-implied baseline is not exempt from criticism that stems primarily from the baseline's vulnerability to forecasting errors and the reliance on model assumptions.

We incorporate the specificity of the model-implied baseline into the revenue function, accounting for the fact that the reference level ($dB(t)$) can fluctuate across time according to the projections of the model used:

$$\pi(d(t)) = P^{cc}(t)d(t) - (a_1 d(t) + a_2 d(t)^2) + P^R(t)(dB(t) - d(t))^+ \tag{11}$$

Compared to the methodology of the historical baseline (Equation (10)), the key difference in the model-implied approach is the modification of the baseline level from a static threshold (dB) to a dynamic one ($dB(t)$). In our model, $dB(t)$ is chosen to match the estimated deforestation pattern of the BaU scenario, such that

$$dB(t) = d_{\text{BaU}}(t) \quad \forall\, t \in [0, T] \tag{12}$$

where $d_{\text{BaU}}(t)$ is the optimal deforestation in the BaU scenario.

2.2.4. Fixed corridor

The corridor approach has been first proposed by Schlamadinger et al. (2005), and then reformulated jointly in 2006 by the Joanneum Research Institute, the Union of Concerned Scientists, the Woods Hole Research Center, and the Instituto de Pesquisa Ambiental da Amazonia (Griscom et al. 2009). This methodology modifies the historical baseline approach, by replacing the fixed threshold with a corridor whose bounds are computed as levels below and above the average past deforestation rate.

In this paper, we analyse the so-called *corridor 2* methodology,[13] whereby the possible deforestation range is divided into three regions: (1) deforestation levels above the upper boundary do not receive any REDD payments; (2) rates below the lower boundary are entirely eligible for REDD permits, as they would under a fixed-baseline scheme; and (3) deforestation levels within the corridor are discounted proportionally to the distance from the upper boundary, such that rewards are larger when deforestation approaches the lower bound, up to full payments if this lower bound is reached, and conversely, rewards are smaller for deforestation rates close to the upper bound, down to no payment if the upper bound is reached.

The corridor approach attempts to address an important feature of deforestation, namely its frequent fluctuations over time. Movements are usually caused by shifts in key market parameters, such as commodity prices, interest rates, or climate impacts (Joanneum Research Institute 2006). The corridor reward system admits that avoiding deforestation in boom years implies higher opportunity costs, and is, therefore, more difficult to sustain than conservation efforts in years of medium to low timber and agriculture prices. With the corridor system, the landowner is encouraged to keep deforestation rates close to the average historical level, and is rewarded (although modestly) even if slightly above it. The corridor could also be useful when measurement errors hinder the estimation of the historical baseline. The corridor creates an 'error' band around the threshold, advantageous in the absence of incomplete information about past deforestation rates. In the words of Joanneum Research Institute (2006), the 'corridor approach reduces the risk of missing a single-level target'.

With the corridor approach for REDD, the shape of the profit function reflects the design of the reward programme:

$$\pi(d(t)) = P^{cc}(t)d(t) - (a_1 d(t) + a_2 d(t)^2) + P^R(t)w\big(dB^U - d(t)\big)^+ \tag{13}$$

where $dB^L = (1-x)dB$ and $dB^U = (1+x)dB$ represent the lower and upper bounds of the corridor, respectively, dB is the historical deforestation rate, and x the corridor width. $w \in [0, 1]$ is the weight (discount factor) imposed by the corridor. In Equation (13), the third term represents the income generated by the REDD project. The weighting system works as follows:

$$w = 1 - \frac{(d(t) - dB^L)^+}{dB^U - dB^L} = \begin{cases} 1 - \dfrac{d(t) - dB^L}{dB^U - dB^L}, & \text{if } \mathrm{d(t)} > dB^L \\ 1, & \text{if } \mathrm{d(t)} \leq dB^L \end{cases}$$

If the deforestation rate lies within the corridor ($d(t) \in (dB^L, dB^U)$), a linear weighting procedure is activated: on one hand, fewer permits will be received than the difference between the deforestation rate and the upper boundary ($w < 1$). On the other hand, deforestation rates below the lower boundary are rewarded full permits ($w = 1$). The last term in the REDD income, $(dB^U - d(t))^+$, ensures that rewards are received only for deforestation rates below the upper bound of the corridor.

2.2.5. *Variable corridor*

Similar to the difference between the static historical baseline and its dynamic model-implied counterpart, we suggest to modify the fixed-corridor baseline by giving it a dynamic feature. The *variable* corridor replaces the constant lower and upper corridor bounds with time-varying levels, established below and above the deforestation rate of the dynamic BaU scenario. To the best of our knowledge, this is the first time this baseline approach is proposed.

The variable corridor aims at bringing together the strong points of both the model-implied and the fixed-corridor baselines. First, linking corridor bounds to the BaU deforestation trend is expected to offer not only a dynamic but also a forward-looking perspective on deforestation paths, more likely to ensure additionality. Second, the corridor reward system should be able to better deal with estimation errors of the BaU deforestation, and account for periodic fluctuations in deforestation levels, similarly to the fixed corridor. The revenue function follows the methodology of the fixed corridor, but introduces dynamic corridor bounds:

$$\pi(d(t)) = P^{cc}(t)d(t) - (a_1 d(t) + a_2 d(t)^2) + P^R(t)w(t)\big(dB^U(t) - d(t)\big)^+ \tag{14}$$

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Table 1. REDD revenues under different baseline methodologies.

	Single threshold	Corridor
Static	$RR^{\mathrm{H}}(t) = P^R(t)(dB - d(t))^+$	$RR^{\mathrm{Cf}}(t) = P^R(t)\omega(dB^U - d(t))^+$
Dynamic	$RR^{\mathrm{MI}}(t) = P^R(t)(dB(t) - d(t))^+$	$RR^{\mathrm{Cv}}(t) = P^R(t)\omega(t)(dB^U(t) - d(t))^+$

Note: H stands for historical baseline, MI for model implied, Cf for fixed corridor, and Cv for variable corridor.

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where the weighting factor is time varying due to the dynamic corridor bounds, with $w(t) = 1 - \frac{(d(t) - dB^L(t))^+}{dB^U(t) - dB^L(t)}$, $dB^L(t) = (1 - x)dB(t)$, $dB^U(t) = (1 + x)dB(t)$, $dB(t) = d_{\mathrm{BaU}}(t)$, and x the corridor width.

Summing up, in this paper we analyse four different REDD scenarios, namely two static and two dynamic, allowing for either a single-threshold or a corridor approach. While the static baselines are based on historical estimations of the deforestation rate, and are therefore retrospective, the dynamic baseline types are based on estimations of future deforestation trends, and are prospective. We denote the single-threshold approaches as H – the historical – and MI – the model implied. The fixed and variable corridors are labelled Cf and Cv, respectively, hereafter. To summarise, the REDD revenues ($RR(t)$) of each baseline methodology are presented in Table 1.

We solve for the optimal deforestation path under the BaU scenario and the four different baselines.[14] We tackle the non-linearity in the profit function with the help of a numerical approach (see the Appendix).

2.3. Model calibration

Our model is general enough to accommodate the characteristics of many regions where REDD could be implemented. For the numerical application, we take here the view of a forest owner from Peru. As the sensitivity analysis shows, the results are robust and generalisable to different regions of the world (see the Appendix).

Peru is an important REDD candidate in terms of forest resources[15] and market volume.[16] The annual deforestation rate for 1990–2005 is estimated at 0.14%, remaining at low levels relative to its neighbouring countries (FAO 2005). However, more recent estimates show that during 2000–2010 deforestation rates experienced an increasing trend,[17] which is predicted to persist in the near future mainly due to cropland expansion in the Andes (Wassenaar et al. 2007). Several local projects developing REDD credits are currently in the implementation phase in Peru[18] (Hajek et al. 2011; Entenmann and Schmitt 2013).

The list of parameters used for model fitting and their sources are presented in Table 2. In our model, the average deforestation rate obtained in the BaU scenario is about 200 ha/year. We allow the historical baseline level (dB) to vary in a large interval (between 1 ha and 500 ha per annum), in order to cover a broad spectrum of scenarios. While REDD credits are granted in terms of tons of CO_2 reduced per year, we present our results in terms of hectares of avoided deforestation. We convert the deforested area into tons of carbon emitted with the help of a parameter (Ω) whose value for Peru can be found in the OSIRIS model for the above and below ground biomass carbon and for soil carbon (Busch et al. 2009). Another converter (ψ) transforms the quantity of tons of carbon emitted into tons of CO_2 emitted (Assante 2011).

Table 2. Calibration parameters for the numerical solution.

Parameter	Explanation	Value	Source
$P^{cc}(0)$	Composite commodity price	500 Eur/m^3	ITTO (2010)
δ	Growth rate of $P^{cc}(t)$	2.3% per annum S.A. [0, 0.4]% per annum	ITTO (2010)
λ	Eur/m^3 to Eur/ha	158 m^3/ha	Penman et al. (2003)
$P^R(0)$	REDD permit price	5 Eur/tCO_2	Diaz et al. (2011)
γ	Growth rate of $P^R(t)$	2.5% p.a. S.A. [0, 0.4]% per annum	Diaz et al. (2011)
Ω	ha to tC emitted	179 tC/ha S.A. [50, 200] tC/ha	Busch et al. (2009)
ψ	tC to tCO_2	3.67 tCO_2/tC	Assante (2011)
a_1	Cost parameter 1	3.3198 Eur/ha	Angelsen (1996), Verissimo et al. (1992)
a_2	Cost parameter 2	798.0811 Eur/ha^2	Angelsen (1996), Verissimo et al. (1992)
r	Discount rate	2% per annum S.A. [0, 0.1]% per annum	–
dB	Historical baseline	200 ha per annum S.A. [1, 500] ha per annum	–
dB^U	Corridor upper boundary	$(1 + x)$dB ha	–
dB^L	Corridor lower boundary	$(1 - x)$dB ha	–
x_0	Initial corridor width	0.1	–
x	Corridor width	[0.1, 0.9]	–
T	Time horizon	100 years	–

Note: The table captures values used for the calibration of the model parameters. S.A. stands for values used in the sensitivity analysis.

With the help of the parameter λ, we express the price of the composite commodity from Eur/m^3 into Eur/ha, relying on the IPCC Good Practice Guide LULUCF (Penman et al. 2003). The initial price of the commodity ($P^{cc}(0)$) and its growth rate (δ) are computed for the Peruvian market from the Annual Review and Assessment of the World Timber Situation (ITTO 2010). We use the State of the Forest Carbon Markets 2011 (Diaz et al. 2011) to set the initial REDD permit price ($P^R(0)$) and its growth rate. In our calibration, the growth rate of the REDD permit price is above the growth rate of the composite commodity price ($\delta > \gamma$). As a robustness check, we ran the analysis allowing for the opposite relationship ($\delta \leq \gamma$). This change impacts the amount of avoided deforestation, but does not modify the ranking of the baselines.

The chosen level for the discount rate (r) is 2%, placing it slightly lower than the growth rates of the composite commodity and the permit prices; we make here the assumption that forest exploitation and REDD bring higher financial benefits than saving at the discount rate.[19] In reality, discount rates in developing countries take usually larger values and vary widely over time (see the Appendix). Nonetheless, the sensitivity analysis shows that the ranking of baselines is consistent across different values of the discount rate ($r \in [0, 0.1]$).

Finally, for the calibration of the production cost, we adapt the cost function of Angelsen (1996), calibrating it to data from Verissimo et al. (1992) for the Amazonian forest.

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Table 3. Performance indicators of baseline scenarios.

Indicator	Definition	Formula
(1) Effectiveness (E_1)	Avoided deforestation from BaU (%)	$E_1^i = \frac{S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^i}{S_{\mathrm{Tot}}^{\mathrm{BaU}}}$ $S^i{}_{\mathrm{Tot}} = \int_0{}^T d^i(t)dt$
(2) Landowner's welfare (E_2)	Change in income from BaU (%)	$E_2^i = \frac{\Pi_{\mathrm{Tot}}^i - \Pi_{\mathrm{Tot}}^{\mathrm{BaU}}}{\Pi_{\mathrm{Tot}}^{\mathrm{BaU}}}$ $\Pi_{\mathrm{Tot}} = \int^T{}_0 e^{-rt}\pi(d^i(t))dt$
(3) Efficiency (E_3)	Average cost of avoiding 1 ha of deforestation from BaU (Eur/ha)	$E_3^i = \frac{SRR^i}{S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^i}$ $SRR^i = \int^T{}_0 e^{-rt} RR^i(t)dt$

Note: Three measures of REDD performance under different baselines are computed. $d(t)$ is the deforested area, $\pi(t)$ the total income from land, $RR(t)$ the REDD revenue at time t, and $i \in \{\mathrm{H, MI, Cf, Cv}\}$; BaU: business-as-usual, H: historical, MI: model implied, Cf: fixed corridor, Cv: variable corridor.

2.4. *Performance indicators*

We evaluate the performance of REDD programmes under different baseline methodologies with the help of three indicators, in line with the *3E Criteria* proposed by Stern (2008).[20] The performance measures we consider are: effectiveness, landowner's welfare, and efficiency, as detailed in Table 3. First, the effectiveness indicator E_1 measures the avoided deforestation, and the inherent saved emissions. It quantifies the difference between the deforested area of BaU (no REDD) and the different baseline scenarios for REDD, being therefore a measure of additionality. Second, we measure the financial co-benefits of REDD with the help of the E_2 indicator, which quantifies the percentage change in landowner's income due to joining REDD. Finally, the efficiency indicator E_3 provides an estimate of the average cost of forest preservation per hectare of avoided deforestation. It divides the total received REDD revenues by the number of hectares of forest saved under each baseline type compared to the BaU scenario. Here, the cost of each baseline scheme reflects realised (additional) savings in emissions.

3. Results

This section presents the optimal deforestation paths for the BaU and the four REDD baseline approaches, and discusses the implications for baseline choice. Section 3.1 first ranks the baselines according to their performance, and then explains the observed differences by analysing the financial incentives offered by each baseline methodology. At the end of the section, we check the robustness of the baseline ranking to changes in key parameters. Section 3.2 relaxes the initial assumptions regarding corridor bandwidth and symmetry, and underlines possible design adjustments to increase baseline performance. Section 3.3 extends the analysis of baseline performance to technical, social, and environmental aspects of REDD.

3.1. *A first comparison*

We solve for the optimal deforestation paths under the BaU and the four REDD baselines (see Figure 1). With our initial calibration, under each baseline scheme the optimal deforestation path is increasing in time, as agricultural activities become more attractive due to rising composite commodity prices.[21] We compare the performance of the baseline methodologies

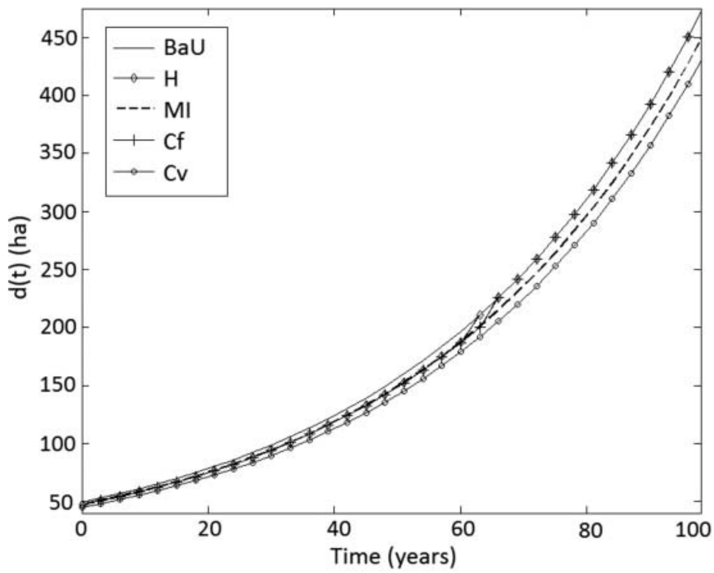

Figure 1. Optimal deforestation paths under BaU and different REDD baselines.
Note: H stands for historical baseline, MI for model implied, H for historical, Cf for fixed corridor, and Cv for variable corridor. The historical deforestation rate (dB) is 200 ha/year. Corridor width is $x = 0.1$.

based on the indicators introduced in Section 2.4. Table 4 shows that the baselines differ in their performance, with each indicator revealing a new ranking of baselines.

First, we compare the baselines in terms of the ability to reduce deforestation. Figure 1 is illustrative of the effectiveness of REDD. In all baseline scenarios, the area of deforested land remains lower or equal to the BaU case; over the aggregated time horizon, REDD programmes are effective in reducing deforestation.[22] However, the reduction in deforestation does not hold at all moments of time for the static baselines: our dynamic model shows that keeping reference levels constant while the opportunity costs of deforestation increase will determine the forest owner to opt out of the REDD project and follow the BaU path. This sheds light on the limited effectiveness of the static baselines, as opposed to the prospective ones that offer continued incentives for reducing deforestation. We argue that, with their temporary effectiveness, static baselines face higher non-permanence risks than dynamic baselines. Analysing the E_1 indicator, we indeed observe that the variable corridor achieves the best results, and it is followed at quite some distance by the model-implied baseline. The fixed-corridor and the historical baselines lag far behind in terms of effectiveness.

Table 4. Indicators of REDD performance under different baselines.

Baseline	Effectiveness E_1 (%)	Welfare E_2 (%)	Efficiency E_3 (Eur/ha)
H	1.54	2.26	73,096.66
MI	4.77	0.23	4,680.18
Cf	1.76	2.76	78,043.75
Cv	9.08	0.92	9,318.13

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Second, imposing no liabilities for deforestation rates above the baseline, all scenarios have a positive impact on landowner's welfare compared to the BaU case (E_2). The increase in welfare across all baselines points to the ability of REDD to foster the voluntary opting-in of candidate countries, and alleviates some of the concerns with the need of additional enforcement measures. In particular, the static baselines prove to be more generous: the fixed corridor is the most attractive for the landowner, followed closely by the historical baseline. The remaining two baselines achieve only modest changes in welfare, with the model-implied baseline being the last ranked.

Third, in terms of cost-efficiency (E_3), the prospective baselines strongly outperform the static ones: the model-implied baseline is the top performer, with the variable corridor in the second position. The historical and fixed-corridor baselines require almost 20 times higher costs than MI.

3.1.1. *The incentive structure of the baselines*

In order to understand what drives the difference in baseline performance, we compare the incentive structure of the four baseline methodologies. To ease the comparison, we explicit the REDD revenues at different ranges of the deforestation rate (see Table 5). In particular, within the corridor we define the deforestation rate in terms of the reference level (dB, $dB(t)$), the corridor width (x), and a variable y, with $y \in (0, x)$, such that

(1) when $d(t) \in (dB^L, dB]$, we define $d(t) = (1 - x + y)dB$ for the Cf case, and $d(t) = (1 - x + y)dB(t)$ for Cv;
(2) when $d(t) \in (dB, dB^U)$, $d(t) = (1 + y)dB$ for the Cf case, and $d(t) = (1 + y)dB(t)$ for Cv, with $dB(t) = d_{\mathrm{BaU}}(t)$.

To account for possible misestimations in the BaU deforestation path and to increase participation rates, the corridor approaches reward landowners for choosing deforestation rates below an upper corridor bound, which is set above the corresponding single threshold ($dB^U = (1 + x)dB$, $dB^U(t) = (1 + x)dB(t)$, with $x > 0$). We observe from Table 5 that by design, for the same deforestation rate, a corridor approach always gives larger or equal financial incentives to participate in REDD to the corresponding single-threshold approach. For all $t \in [0, T]$

$$RR^{\mathrm{H}}(t) \leq RR^{\mathrm{Cf}}(t) \tag{15}$$

$$RR^{\mathrm{MI}}(t) \leq RR^{\mathrm{Cv}}(t) \tag{16}$$

The ranking of REDD payments influences the effectiveness of the baselines. Larger REDD revenues decrease the opportunity costs of deforestation, bringing stronger incentives to take part in REDD and keep deforestation below the baseline. Any decrease in deforestation will inevitably take place below $d_{\mathrm{BaU}}(t)$.[23] It follows that relations (15) and (16) hold also for effectiveness with unchanged signs:

$$E_1^{\mathrm{H}} \leq E_1^{\mathrm{Cf}} \tag{17}$$

$$E_1^{\mathrm{MI}} \leq E_1^{\mathrm{Cv}} \tag{18}$$

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Table 5. REDD revenues ($RR(t)$) according to the range of the deforestation rate.

Static baselines				
	$d(t) \in [0, dB^L]$	$d(t) \in (dB^L, dB]$	$d(t) \in (dB, dB^U)$	$d(t) \geq dB^U$
H	$P^R(t)(dB - d(t))$	$P^R(t)(x - y)dB$	0	0
Cf	$P^R(t)((1 + x)dB - d(t))$	$P^R(t)\left(2(x - y) + \frac{y^2}{2x}\right)dB$	$P^R(t)\frac{(x-y)^2}{2x}dB$	0
Dynamic baselines				
	$d(t) \in [0, dB(t)^L]$	$d(t) \in (dB(t)^L, dB(t)]$	$d(t) \in (dB(t), dB(t)^U)$	$d(t) \geq dB(t)^U$
MI	$P^R(t)(dB(t) - d(t))$	$P^R(t)(x - y)dB(t)$	0	0
Cv	$P^R(t)((1 + x)dB(t) - d(t))$	$P^R(t)\left(2(x - y) + \frac{y^2}{2x}\right)dB(t)$	$P^R(t)\frac{(x-y)^2}{2x}dB(t)$	0

Finally, we analyse the impact of higher REDD revenues on efficiency. Our efficiency indicator (E_3) is defined as a measure of total REDD revenues divided by the hectares of reduced deforestation below BaU. Therefore, an increase in REDD revenues will have a double (yet opposed) impact on efficiency. First, higher $RR(t)$ lead to lower efficiency (higher E_3). Second, higher $RR(t)$ raise effectiveness (avoided deforestation), increasing efficiency (lower E_3). As can be observed from Table 4, the effect on welfare dominates the effect on effectiveness.[24] It follows that the single-threshold approaches, with lower welfare increases, are more efficient than the corresponding corridor approaches, with higher welfare increases. That is,

$$E_3^{\mathrm{H}} \leq E_3^{\mathrm{Cf}} \tag{19}$$

$$E_3^{\mathrm{MI}} \leq E_3^{\mathrm{Cv}} \tag{20}$$

Summing up, we have shown that the corridor approaches dominate the corresponding single-threshold approaches in terms of effectiveness and welfare increase, but lag behind in terms of efficiency. If sufficient funding is available, which remains to be seen, we argue that REDD promoters should opt for the corridor approach instead of the single-threshold one, in order to achieve the needed reductions in emissions.

3.1.2. *Sensitivity analysis*

REDD initiatives are currently being designed in a plethora of tropical countries, with several projects being already in the implementation phase (Angelsen 2010). In particular, Norway − through its International Climate and Forest Initiative (NICFI) − contributes to different multi- and bi-lateral REDD initiatives in several countries, including Brazil, Democratic Republic of Congo, Guyana, Indonesia, and Tanzania. These countries are distinct in terms of forest types, stages in the forest transition, and national forestry policies, apart from a large diversity in the economic, social, and political contexts. To reach the REDD goals, NICFI recognises the need to design projects that account for national and subnational differences (NIFCI 2011). For instance, the Guyana−Norway cooperation agreed on a baseline that reflects both the historical average deforestation in Guyana and the mean deforestation rate in developing countries. Since Guyana had historically very low deforestation rates compared with other developing countries, the computed reference level is much higher than the country's past average deforestation rate. To allow for positive but limited increases in deforestation, payments are reduced linearly for deforestation rates that exceed a certain threshold, similarly to the fixed-corridor approach.

To be able to generalise our findings outside the region of Peru, we test the robustness of our results across different settings. We focus on several key calibration parameters, describing the forest type (the carbon content Ω), the crediting threshold of the static baselines (dB), the time preference of the forest owner (the discount rate r), and the variables describing the opportunity costs of deforestation and the received REDD financial incentives (the growth rates of the composite commodity (δ) and REDD permit prices (γ)). The detailed analysis can be found in the Appendix.

We find that the ranking of baselines is robust to different settings. The variable corridor continues to be the most effective in reducing deforestation. The fixed corridor offers the highest increase in welfare from BaU. The model-implied baseline is the most efficient, having the lowest costs per hectare of avoided deforestation. The sensitivity analysis underlines the importance of understanding the benefits of the variable-corridor

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approach, whose performance can outpace significantly the other baselines, depending on the characteristics of the region where REDD is being implemented.

3.2. Corridor bandwidth and symmetry

When large uncertainties surround the BaU deforestation rate, or high variability in opportunity costs is to be expected, one might be tempted to advocate a corridor approach with a larger bandwidth, such that a broader range of deforestation rates would be accounted for in the REDD payments. The corridor bandwidth should in this case be carefully chosen, to provide effective incentives for forest protection and, at the same time, achieve cost-efficiency.

With this motivation, we test the sensitivity of baseline performance to two key adjustments to the corridor methodology, namely corridor wideness and symmetry. We allow for increasing bandwidths ($x \in [0.1, 0.9]$) that reflect different reward magnitudes granted for reducing deforestation. Additionally, we check the variation in performance when allowing for asymmetric corridors. Namely, we consider both an upward- and a downward-biased corridor. For the variable corridor, bounds are set such that

(1) in the upward-biased case, $dB^L(t) = (1 - x_0)dB(t)$ and $dB^U(t) = (1 + x)dB(t)$;
(2) in the downward-biased case, $dB^L(t) = (1 - x)dB(t)$ and $dB^U(t) = (1 + x_0)dB(t)$;

where $dB(t) = d_{\mathrm{BaU}}(t)$, $x \in [0.1, 0.9]$, and x_0 is fixed, with $x_0 = 0.1$. The same applies for the fixed corridor, but $dB(t)$ is replaced as usually by the constant dB. On one side, the upward-biased corridor approach raises the upper bound of the corridor, leading to an extension of the range of deforestation rates eligible for REDD revenues. This type of asymmetric corridor is in line with the proposal of Schlamadinger et al. (2005) who suggest setting the upper bound of the corridor so high that it minimises the probability that the deforestation rate will exceed this limit. In contrast, the downward-biased approach takes down the lower bound of the corridor, imposing therefore heavier discounts on REDD rewards for deforestation rates in the range $(dB^L, dB]$ $((dB^L(t), dB(t)])$ for the fixed (variable) corridor.

Figure 2 displays the performance results of the variable corridor. The change in the performance of the fixed corridor follows a similar pattern (see Figure E.1 in the Appendix). First, some effectiveness is always achieved ($E_1 > 0$), for all corridor bandwidths

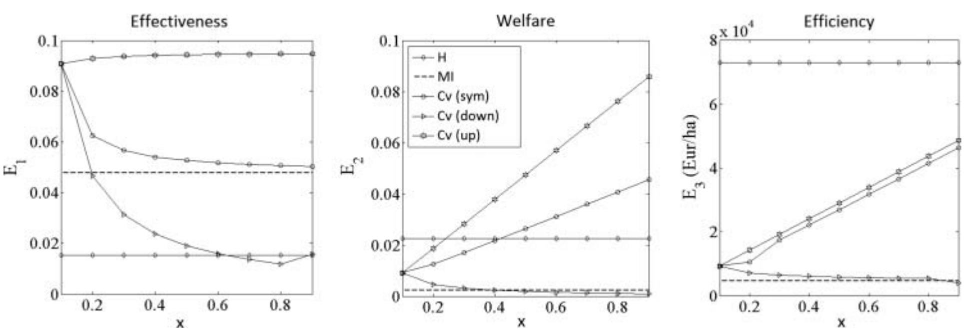

Figure 2. Performance of the variable corridor at different corridor widths.
Notes: The figure captures the performance of the variable corridor across different corridor bandwidths. The performance is compared to the historical and the model-implied baselines. Considered corridors are symmetric (*sym*), upward (*up*), and downward biased (*down*).

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and all symmetry alternatives. Figure 2 shows that, as bandwidth increases, effectiveness is higher for the upward-biased corridors, but decreasing for symmetric and downward-biased corridors. Second, increasing the corridor bandwidth achieves higher welfare improvements for the symmetric and upward-biased corridor approaches. Downward-biased corridors exhibit decreasing welfare for wider corridors. Third, cost-efficiency decreases for symmetric and upward-biased corridors, and improves slightly for the downward-biased corridor when increasing the corridor width.

3.2.1. The incentive structure of (a)symmetric corridors

The three symmetry scenarios provide distinct financial incentives, causing differences in performance. The upward-biased corridor is by design the most generous one, followed by the symmetric, and then the downward-biased corridor, i.e. $RR^{up}(t) \geq RR^{sym}(t) \geq RR^{down}(t)$ for all bandwidths.[25] Moreover, an increase in the corridor bandwidth (x) impacts the REDD revenues differently, depending on the symmetry assumption. The overall impact of an increase in bandwidth is twofold: (1) a linear impact on the number of REDD credits received for keeping deforestation rates below the upper corridor bound, i.e. on $n = dB^U(t) - d(t)$ and (2) a non-linear impact on the weight ($\omega(t)$) provided by the corridor (see Table 6).

The upward-biased approach achieves increasing welfare at larger corridor widths. With an increase in x, both the number of REDD credits received and the weight provided by the upward corridor increase. As captured in Figure 2, welfare and effectiveness change in the same direction when x increases, but the large increase in welfare obtained at wider corridors is accompanied by only modest improvements in effectiveness that have the tendency to flatten out as x increases. The stronger financial motivation has a diminishing effect on forest protection.

Downward-biased corridors exhibit negative partial derivatives with respect to x, showing that here welfare improvements from BaU are lower for wider corridors. Larger bandwidths decrease welfare and, as expected, effectiveness.

The symmetric-corridor approach achieves higher welfare but lower effectiveness as bandwidth increases. The overall positive impact on welfare follows, as usually, from the fact that its REDD revenues are increasing in the corridor bandwidth. However, although the total impact is positive, the linear and non-linear effects have opposite signs (Table 6).

Table 6. Sensitivity of REDD revenues to corridor bandwidth and deforestation rate in the case of the variable corridor. $RR(t) = P^R(t)\omega(t)n$, with optimal $d(t) \in (dB^L(t), dB)$.

Symmetry	Linear impact on REDD credits $\frac{\partial n}{\partial x}$	Non-linear impact on weight $\frac{\partial \omega(t)}{\partial x}$	Overall impact on REDD revenues $\frac{\partial RR(t)}{\partial x}$	Second order impact on REDD revenues $\frac{\partial^2 RR(t)}{\partial x \partial d(t)}$
Upward biased	+	+	+	−
Symmetric	+	−	+	+
Downward biased	0	−	−	+

Note: The table captures the sign of the partial derivatives of REDD revenues with respect to corridor width (x) and deforestation rate ($d(t)$) across different symmetry scenarios for the variable corridor. The optimal deforestation rate stays within the corridor, i.e. $d(t) \in (dB^L(t), dB(t))$. $n = dB^U(t) - d(t)$ is the number of REDD credits awarded, $\omega(t) = 1 - (d(t) - dB^L(t))/(dB^U(t) - dB^L(t))$ is the weight imposed by the corridor approach, and the lower and upper bounds of the corridor ($dB^L(t)$, $dB^U(t)$) vary across the three corridor symmetry assumptions. The computations are detailed in the Appendix.

As bandwidth increases, the landowner benefits, on one hand, by receiving more REDD credits (higher n), but loses, on the other hand, from stronger discounts imposed by the weighting factor (lower $\omega(t)$). The impact on effectiveness is confirmed when analysing the joint sensitivity of REDD revenues to the deforestation rate and corridor bandwidth (see column (4) in Table 6). The increase in profits due to an increase in x is higher at larger $d(t)$, as indicated by the positive second-order partial derivatives. At larger corridor bandwidths, it benefits the landowner to increase $d(t)$, and therefore reduce effectiveness.

Summing up, with a lack of confidence in the estimates of the BaU deforestation, or with anticipated high seasonality in deforestation rates, wider corridors might need to be accommodated, in a way that forest protection is still incentivised. Our results show that increasing the corridor bandwidth ensures a higher effectiveness of reducing deforestation only in the upward-biased corridor design, and is counter-beneficial for symmetric and downward-biased cases. Both fixed and variable corridors benefit most from having an upward-biased corridor reward system of moderate bandwidth ($x = 0.4$, 0.5), which guarantees strong effectiveness and welfare results, at low efficiency losses.

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3.3. Extended criteria for baseline evaluation

Our analysis so far has highlighted three baseline alternatives with strong performance results: the model-implied (MI), the upward-biased fixed corridor (Cf(up)), and the upward-biased variable corridor (Cv(up)), with each baseline alternative performing best in a different area.

Although the three performance indicators considered so far capture the most important economic aspects of the alternative baselines, other factors play an equally important role in the REDD implementation process. In order to achieve a more holistic understanding of the baseline characteristics, we complement the economic evaluation with a multi-tier analysis focusing on the environmental, technical, and social performance of the baselines. Based on the study of Huettner et al. (2009), we select five new criteria whose fulfilment can be easily evaluated for our baselines, namely easiness of implementation, low data requirements, accounting for business cycles, accounting for opportunity costs, and incentivising a reduction in losses from estimation errors.

The fulfilment of these additional qualitative factors cannot, however, be quantified in the same manner as our three initial economic indicators. For this reason, we proceed by giving each baseline type a score[26] representing a rough estimation of how well it is expected to fulfil the performance criteria relative to the other baselines. The scores awarded to each baseline for the three initial indicators and the new qualitative aspects are presented in Figure 3. While the economic analysis (based on E_1, E_2, and E_3) favoured each of the baselines for a different criterion, the integrative analysis sets the four baselines further apart, highlighting stronger differences.

One of the new criteria reveals a strong point of the historical baseline (H). REDD projects, especially in their initial phase, need to be designed as contracts with few and clear requirements in order to encourage the participation of diverse parties and create momentum for the development of such forest protection initiatives worldwide. The historical baseline is likely to benefit from the highest ease of implementation among the considered methodologies. If data availability is not an issue, policy-makers will be required low efforts for baseline computation and landowners will be provided with contract guidelines they can easily relate to. Together with the fact that historical deforestation rates have some predictive power for short- to medium-term deforestation (Angelsen

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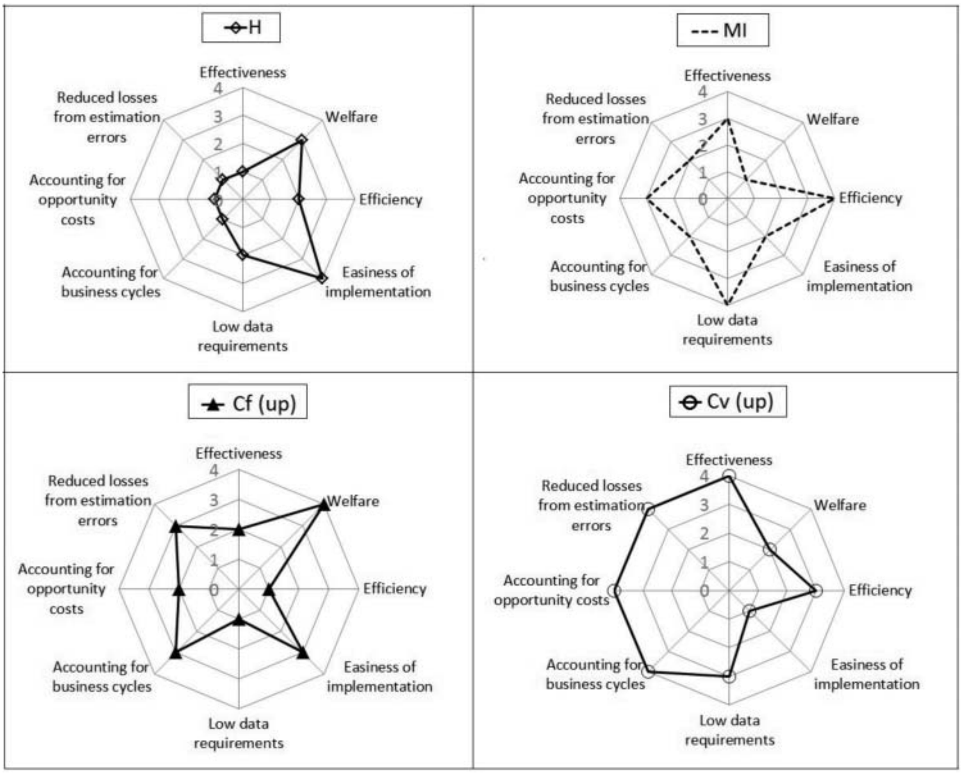

Figure 3. Integrated performance of baseline approaches.

et al. 2009), the ease of implementation explains why current REDD initiatives have opted to rely on the historical baseline for computing reductions in deforestation.

The model-implied (MI) baseline provides rewards for reductions below the estimated counterfactual deforestation, accounting for future opportunity costs. In our model, its computation does not rely on the availability of data records of past deforestation; instead, it requires information regarding current agricultural prices and estimations of the future trend in prices. In this context, we argue that the MI has comparatively less data restrictions than all the other baseline methodologies.[27] Moreover, if the estimation of the BaU deforestation path is truthful, the implementation of REDD with the MI baselines favours additionality. Figure 3 reminds us that this baseline stands out in terms of cost-efficiency, as highlighted in Section 3.1. This can be a strong point in favour of the MI baseline, especially if future REDD rewards will be linked with compliance carbon markets.

The upward-biased fixed corridor (Cf(up)) modifies the historical baseline by replacing the single-threshold with a corridor approach. Section 3.2 showed that selecting an upward-biased corridor can improve its effectiveness and welfare performance. Indeed, the upward-biased corridor approach is the most attractive for the landowner from a welfare perspective. Despite large financial transfers, the effectiveness and efficiency of the Cf(up) remain limited.

Overall, the integrative analysis appears to give highest support to the variable corridor approach. The upward-biased variable corridor (Cv(up)) is the most effective in reducing deforestation below BaU levels (see Section 3.1). Being a prospective method, based on expectations regarding the future movement of timber and agriculture prices, as well as REDD permit prices, the Cv(up) has a better ability to reflect the opportunity costs faced by the landowner. Additionally, the corridor design brings two advantages. First, the scheme offers REDD compensation also for deforestation rates that come close to the time-varying baseline, even if not strictly below it; this accommodates possible future business cycles and ensures (modest) positive REDD revenues should the economy be expanding (when opportunity costs are high). Second, replacing the single-threshold approach by a corridor approach, and introducing the weighting system for deforestation rates inside the corridor, the baseline has the ability to reduce losses due to misestimation of the BaU baseline (Joanneum Research Institute 2006).

Summing up, designing a baseline methodology that achieves all REDD goals simultaneously proves to be highly challenging. Indeed, the analysed baselines exhibit strong attributes in different areas. For its ability to enhance environmental and economic performance, we consider the upward-biased variable corridor to be the best candidate for achieving the most important REDD goals.

3.3.1. (Mis)estimation of BaU deforestation

Two delicate issues require further thought. The first one touches on the issue of additionality. REDD aims to reward reductions in deforestation below BaU levels. One limitation of our analysis is that it is placed in a deterministic setting, where the BaU deforestation path is known. However, in reality many variables of the decision environment are in fact stochastic, such as commodity and REDD prices, and asymmetries in information might lay between REDD promoters (who evaluate emission reductions) and forest owners (who benefit from REDD payments). This surrounds the estimation of the BaU deforestation path with significant uncertainties.

REDD projects implemented based on misspecified BaU deforestation levels can provide undesired incentives to forest owners. Errors in the estimation of the BaU would directly impact the financial incentives of the prospective baselines, i.e. model-implied and variable corridors.[28] We investigate this hypothesis and solve for the optimal deforestation path when the baseline methodology relies on a misspecified BaU path. We define the estimated BaU deforestation as

$$d^{E}_{\mathrm{BaU}}(t) = (1 + \epsilon) d_{\mathrm{BaU}}(t) \tag{21}$$

where d_{BaU} is the true deforestation path when no REDD programme is in place, and ε is the percentage misestimation of the BaU deforestation rate, with $\epsilon \in [-0.05, 0.05]$.

Our results are detailed in the Appendix. First, we find that the performance of the variable-corridor methodology is robust if estimation errors stay within [−5%, +5%] from the true BaU deforestation path. As the estimation errors increase, the effectiveness of the variable corridor decreases; however, within the considered range, the variable corridor remains the most effective in reducing deforestation among the four baseline methodologies, despite the performance loss. Our conclusion that the variable corridor should be the preferred baseline methodology is, therefore, robust.

Second, an underestimation of BaU decreases the performance of the model-implied baseline; for estimation errors below −3%, the landowner will opt out of the REDD project and no reductions in deforestation from BaU will be obtained. On the other hand, small underestimations (above −2%) and overestimations in general do not impact the landowner's deforestation reduction decisions, and the MI remains more effective than the historical or fixed-corridor approaches. This analysis reveals the importance of

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designing baselines that are in line with the future drivers of deforestation. In particular, for forest-rich regions that have historically very low deforestation rates, like the Congo Basin, significantly underestimating the baseline would lead to ineffective REDD programmes. It appears to be less problematic to provide an overestimated baseline than an underestimated one.

3.3.2. REDD permanence

The second key issue concerns permanence. With REDD, the issue of permanence has a different dimension from that on compliance carbon markets, like the EU ETS. There, being restricted to emit less than a pre-specified cap, regulated companies continue with the same business activity, but are given incentives to switch to a more efficient production process.[29] Being costly, the switch is likely not to be reverted, and emission reductions could remain 'permanent'. The situation is not analogous to REDD, where the landowners cannot continue with their current occupation (deforesting for expanding agriculture), but need to stop the expansion if they want to receive payments (they cannot make the cutting down of trees less emission-intensive). REDD payments are offered on a per-period basis, being linked to deforestation flows instead of the remaining forest stocks. Thus, temporary reductions in deforestation can be reverted in later periods, questioning the long-term success of REDD. Moreover, unlike the current voluntary market for REDD permits, the EU ETS is a capped market, where regulated players face penalty costs if their emissions exceed the allowed level.[30] We argue that REDD payments could be contingent on the emissions of the entire owned land parcel, such that all land uses are covered by the regulation umbrella, and more efficient operations are incentivised, similar to the mechanism of the cap-and-trade systems. However, this takes us away from the original REDD concept, and future research could further investigate this topic.

4. Conclusions

REDD programmes target reductions in emissions from deforestation below BaU levels. A key issue of REDD is the establishment of baselines against which reductions in deforestation are measured. This paper assesses the performance of the most frequently proposed baselines: historical, model-implied, and fixed corridors. Additionally, we introduce a new baseline type – the variable corridor.

We solve for the optimal deforestation path in a dynamic setting where REDD projects are available. One of our main findings is that the baseline choice has a significant impact on land-use behaviour. Landowners choose different deforestation paths when incentivised by distinctive baseline methodologies. We believe this point is key for implementing effective REDD programmes.

We first evaluate the selected baselines according to three economic indicators that describe the effectiveness, welfare increases, and cost-efficiency of reducing deforestation. We find that each indicator points to a different baseline as the best performer. Our analysis shows that a preference for strong effectiveness recommends the variable corridor. The fixed corridor provides the highest increase in landowner's welfare above BaU. Efficiency reasons advocate the model-implied baseline.

We then discuss additional environmental, social, and technical aspects important for REDD implementation and the setting of baselines. This analysis highlights stronger differences among the baselines, and reveals that the prospective variable corridor achieves the best trade-off among the economic and environmental REDD goals. Moreover, this

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performance can be boosted by setting the upper bound of the corridor (asymmetrically) high above the estimated BaU deforestation.

We conclude that the current widespread use of the historical baseline may be challenged. Much stronger effectiveness and efficiency could be achieved with the use of a forward-looking baseline, provided that estimation errors do not largely underestimate future deforestation. Additionally, the currently used single-threshold methodology is also not optimal; replacing the single-threshold approach with a corridor formed around the estimated BaU deforestation rate has higher potential of accounting for real opportunity costs and offering continued incentives for reduced deforestation.

Our results offer potential insights for other emission regulation policies, such as the EU ETS. There regulated companies are allocated emission allowances based on their emissions' history, similar to the historical baseline in REDD. Based on our analysis, we expect the EU ETS to benefit also in terms of effectiveness and efficiency from replacing its historical cap with a forward-looking corridor approach. This could potentially address some of the permit overallocation problems, which have persisted since the opening of the EU ETS.

Some additional concerns remain. This paper assumes that REDD funding is achieved through a market-based mechanism. In comparison to voluntary funds, international carbon markets can mobilise much larger amounts of money and favour cost-efficient emission reductions (Angelsen 2008b). However, the weak carbon markets we face nowadays, characterised by low liquidity and permit overallocation, will most probably have difficulties in handling additional amounts of permits coming from the forestry sector. Therefore, when selecting the most appropriate baseline type, one might postpone the implementation of the most effective one in order to avoid drops in permit prices until the stabilisation of the carbon market.

Our analysis has relied on the dynamic setting to check the ability of the different baselines to provide *continued*, not temporary, incentives to reduce deforestation. However, we did not address the issue of resetting reference levels, based on updated information. This would require the setting and solving of the model under conditions of uncertainty, where a decision-maker would readjust the baseline based on newly received information about the deforestation rate of the landowner, and the landowner would subsequently adjust his or her deforestation rate based on the new baseline. This constitutes a very interesting question for future research; it could bring insights into the response of landowners to changes (e.g. tightening) in requirements to reduce deforestation.

Finally, a robust understanding of the deforestation process would require an improved description of the different stakeholders involved in REDD implementation. As Griscom et al. (2009) point out, the selection of reference levels will be based not only on technical and economic considerations, but also on political negotiations among participating countries. REDD projects implemented at the national level will motivate countries to take a strategic position at the negotiation table and try to influence the establishment of crediting levels in their favour. Under these conditions, the adjusted deforestation decision will result in emission reductions of other magnitudes than the ones presented in this study, and might as well reveal a different ranking of baseline approaches. Future research, based on dynamic decision models with multiple players defending contrasting interests, could be relevant for this issue.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Notes

1. While REDD gives priority to reducing emissions from deforestation, REDD+ targets additionally the sustainable management of forests and the enhancement of carbon stocks.
2. These emitters could be found among the European polluting companies that are regulated by the EU ETS and need to comply with emission reduction targets.
3. We thank an anonymous referee for the input.
4. We are thankful to an anonymous reviewer for raising this important point.
5. In the paper of Busch et al. (2009, 2011), the owner will 'opt in' if the REDD revenues are higher than the agricultural rental price and 'opt out' otherwise.
6. Reducing the complexity of the harvesting function, which is not central for comparing the reference levels, allows us to focus on the dynamic choice between maintaining the forest cover and harvesting.
7. Using deterministic processes simplifies the solution to the model, but leaves outside of the scope of our analysis the role and influence of risk on the optimal land allocation decision. Under the hypothesis of a risk-neutral landowner, the presence of risk would have no specific effects. However, in the presence of risk aversion, the decision between preservation and deforestation will be significantly impacted by the relative volatility of the two prices and would favour the strategy giving the smallest cash flow variability.
8. We consider this setting to be in line with the reality of many landowners' decision processes in tropical countries. In Latin America, ownership rights tend to be concentrated in the hands of a few proprietors (Brockett 1990; Borras Jr et al. 2012).
9. This time frame is expected to be aligned with the phases of the EU ETS or the successor of the Kyoto protocol.

10 Out of the 6 baseline methodologies reviewed by Griscom et al. (2009), 5 rely partially or totally on historical reference levels.

11. According to Angelsen (2007), 'The FT describes a sequence where a forested region goes through four stages: (1) initially high forest cover and low deforestation, (2) accelerating and high deforestation, (3) slow-down of deforestation and forest cover stabilisation, and (4) a period of reforestation.'
12. According to Huettner et al. (2009), prospective (forward-looking) methods attempt to model land-use change taking into account the various market drivers. The forecasting can be done by using either analytical, regression or simulation models.
13. The *Corridor 1* method proposes that deforestation rates within the corridor accrue credits that would only be eligible for sale once emissions go below the lower boundary of the corridor (Joanneum Research Institute 2006).
14. The analytical results can be provided by the authors upon request.
15. With about 68 million hectares of tropical forest covering nearly 53% of its territory, Peru is fourth in the global ranking, after Brazil, the Democratic Republic of Congo, and Indonesia. About 89% of the total classifies as primary forest (FAO 2010).
16. According to Diaz et al. (2011), the Peruvian and Brazilian Amazon dominate the forest carbon market, with Latin America accountable for about 60% of the 2010 total primary market volume.
17. The annual change in forest area was −0.22% for 2005–2010 (FAO 2010).
18. Hajek et al. (2011) compare 12 local REDD+ projects in south-eastern Peru, 5 of which were at feasibility and 7 at an early implementation stage at the time of writing.
19. Due to the lengthy decision horizon (100 years), we are constrained to select a low value for the discount rate; otherwise, the discounted value of incomes at later periods of time would be very close to zero, rendering irrelevant the decisions further away in the future. This approach is consistent, for instance, with the work of Gollier (2002).
20. Stern (2008) suggests the evaluation of REDD design proposals with the help of three criteria: effectiveness, efficiency, and equity and co-benefits.
21. In the Appendix, we analyse the case of decreasing deforestation paths, where the growth rate of the agricultural composite commodity is low ($\delta = 0$) (see Figure D.9). We find that the ranking of baselines is robust across regions with different trajectories in the deforestation path.
22. For a more detailed illustration of deforestation paths for each period, see Figure B.3 in the Appendix.
23. $d(t)$ is bounded from above by $d_{\mathrm{BaU}}(t)$, due to extraction cost constraints.

24. For the full demonstration, see the Appendix.
25. For a demonstration, see Table E.1 in the Appendix.
26. The score allocated to each baseline takes values from 1 to 4 (4 is the number of baselines considered for comparison: historical, model-implied, upward-biased fixed corridor, and upward-biased variable corridor), such that for each indicator, a score of 4 is awarded to the baseline believed to be most likely to fulfil the criterion, and a score of 1 to the baseline least likely.
27. This might not always be the case; some proposed forward-looking baselines rely on the historical deforestation average as a starting point for predicting future deforestation rates.
28. Misestimations could also occur in the computation of the historical deforestation rate, impacting the financial incentives provided by the historical and fixed-corridor baselines. In this section, we focus only on estimation errors concerning the BaU deforestation path. In our model, this has no impact on the incentives provided by the historical and fixed-corridor methodologies.
29. This refers to relying on less emission intensive sources of energy, such as renewables or the more common switch from coal to gas for the generation of electricity.
30. We thank an anonymous referee for raising this point.
31. We allow for all possible switching points in the range $[0, T]$.
32. Data source is the OSIRIS v.3-4 spreadsheet, available online at http://sp10.conservation.org/osiris/Pages/overview.aspx.
33. Of course, not the entire territory of Peru is covered with forest and eligible for REDD projects. As mentioned in Section 2.3, Peru has about 68 million hectares of tropical forest, covering nearly 53% of its territory.
34. Various international standards have emerged to distinguish between different forest projects, such as the Panda Standard in China.

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Appendix

A. Optimal deforestation path in the business-as-usual scenario

When no REDD programme is in place, the net revenue of the landowner at time t is given by

$$\pi\Big(d(t)\Big) = P^{cc}(t)d(t) - \Big(a_1 d(t) + a_2 d(t)^2\Big) \tag{A.1}$$

The optimal control problem can be described as follows:

$$\max_{(d(t))_{t\in[0,T]}} \int_0^T e^{-rt}\pi\Big(d(t)\Big)dt \tag{A.2}$$

$$\text{such } \dot{F} = -d(t) \tag{A.3}$$

$$F(0) = F_0 \tag{A.4}$$

We build the current-value Hamiltonian as

$$H^c = \pi\Big(d(t)\Big) - \mu d(t) \tag{A.5}$$

The equations of motion follow immediately:

$$\frac{\partial H^c}{\partial d(t)} : \pi'\Big(d(t)\Big) - \mu = 0 \tag{A.6}$$

$$-\frac{\partial H^c}{\partial F} + r\mu = \dot{\mu} \tag{A.7}$$

$$\dot{F} = -d(t) \tag{A.8}$$

The partial derivative of the Hamiltonian with respect to the forest stock is zero $\left(\frac{\partial H^c}{\partial F} = 0\right)$. We obtain from Equation (A.7) that

$$\dot{\mu} = r\mu \Rightarrow d\mu = \mu r dt \Rightarrow \mu(t) = \mu(0)e^{rt} \tag{A.9}$$

From Equation (A.6) we know that $\pi'(d(t)) = \mu(t)$, which holds for all $t \in [0, T]$. It follows that $\pi'(d(0)) = \mu(0)$. Introducing this result in Equation (A.9), we obtain that

$$\pi'\Big(d(t)\Big) = \pi'\Big(d(0)\Big)e^{rt} \tag{A.10}$$

We explicit Equation (A.10) with the help of the profit function given in Equation (A.1). After some simplifications, the optimal deforestation rate at time t is given by

$$d(t) = d(0)e^{rt} + \frac{P^{cc}(0)(e^{\delta t} - e^{rt}) - a_1(1 - e^{rt})}{2a_2} \tag{A.11}$$

The optimal deforestation at time t depends on the initial deforestation rate ($d(0)$), the discount rate (r), the initial price of the composite commodity ($P^{cc}(0)$) and its growth function (δ), and the parameters of the cost function (a_1, a_2). In order to define the optimal deforestation path, the last element that needs to be defined is the initial deforestation rate ($d(0)$). We iterate over a large grid of possible values and choose the initial deforestation that maximises total profits.

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B. Optimal deforestation path under REDD

The simultaneous presence of REDD rewards for lower-than-baseline and absence of penalties for higher-than-baseline deforestation levels brings discontinuities to the profit function. The resulting non-smoothness in the objective function impedes the application of standard optimisation methods. To overcome this difficulty, we develop a solution approach based on regime switches. This method allows for a break in the continuity of the deforestation path, which would otherwise be forced under the standard Hamiltonian procedure. A smooth deforestation path would not be able to guarantee optimality in the context of a non-smooth objective function. Here, we allow the landowner to decide at each moment of time whether to deforest below or above the reference level, i.e. they make their choice between a *REDD regime* (hereafter Regime 1) and a *BaU regime* akin to BaU (hereafter Regime 2).

One observation is key to solving the optimisation problem: in the absence of stochasticities, the decision regarding deforestation levels at each moment of time can be taken from the beginning for all future periods. While it could be possible in theory that the landowner switches between regimes multiple times, in practice the dynamic requirement at equilibrium ensures smooth evolution for the deforestation path within each regime and limited shifts between regimes over the entire horizon. We begin by explaining the solution approach for the historical and the model-implied cases. Since it requires an additional modification, we present the solution to the corridor scenario at the end of this section.

For the historical and the model-implied baselines, the landowner chooses low deforestation rates and stays in Regime 1 as long as the total benefits from REDD and forest exploitation below the reference level remain higher that the total benefits from forest exploitation above the reference level. Depending on the values of the parameters, the regime switch can occur either from the beginning, somewhere during the lifetime of the maximisation period, or never at all. Formally, the optimisation procedure can be described as follows:

$$\max_{d(t)|t\in[0,T]} \left\{ \int_0^{\tau} e^{-rt}\pi^{R_1}\Big(d(t)\Big)dt + \int_{\tau}^{T} e^{-rt}\pi^{R_2}(d(t))dt \right\} \tag{B.1}$$

with R_1 and R_2 standing for Regime 1 and Regime 2, respectively. τ is the switching time from Regime 1 to Regime 2:

$$\tau = \inf\{t \geq 0 | d(t) \geq dB\} \tag{B.2}$$

We adapt the solution method of Chiang (1992) to allow for regime switches. The current-value Hamiltonian is defined as

$$H^c = \begin{cases} H^{R_1} = \pi^{R_1}(d(t)) - \mu_1(t)d(t), & \text{if } t \in [0, \tau) \\ H^{R_2} = \pi^{R_2}(d(t)) - \mu_2(t)d(t), & \text{if } t \in [\tau, T] \end{cases} \tag{B.3}$$

It is important to underline that if Regime 1 occurs in our parametrisation, it will precede Regime 2, due to the different profit dynamics of the two activities. On one hand, the landowner can gain from intensifying forest exploitation, as long as their inflows do not exceed operating costs. In time, their revenues rise due to the increasing price of the composite commodity. On the other hand, even if revenues from REDD increase due to rising permit prices, these profits are limited, since the deforestation rate is bounded from above by the reference level and from below by zero (we do not allow for reforestation). Therefore, even if initially marginal benefits with REDD could be higher than BaU marginal benefits, this advantage would decrease over time. As a consequence, remaining in Regime 1 could become suboptimal at a certain moment of time (τ), after which the landowner will move to Regime 2.

Figure B.1 captures dominant profits of either REDD or BaU regimes at different deforestation rates. The hashed area represents cases where taking part in the REDD project is optimal, while the grey area symbolises regions where the BaU scenario is optimal. Within each section of the graph, lighter colours stand for higher profit values. As long as the deforestation rate is below the fixed baseline, the optimal regime to choose is the REDD one (see Figure B.2). This holds for initial time periods. As time passes, the overall optimum is to be found in the BaU regime. The two figures

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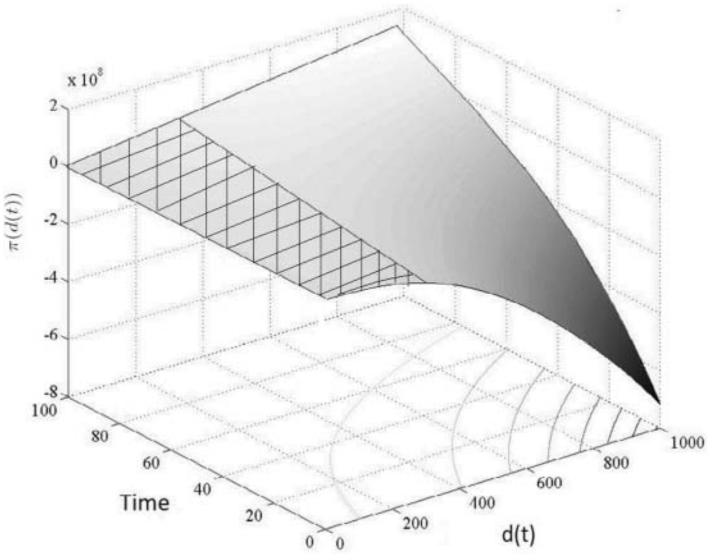

Figure B.1. Land-use revenues.

show that if a regime switch does occur at some moment of time, this switch is expected to take place one time only, as the dominance alternation takes place only once. Moreover, Figure B.1 shows that the REDD regime should precede the BaU regime, since for later periods of time profits are increasing in the deforestation rate and the landowner will be better off opting for the BaU

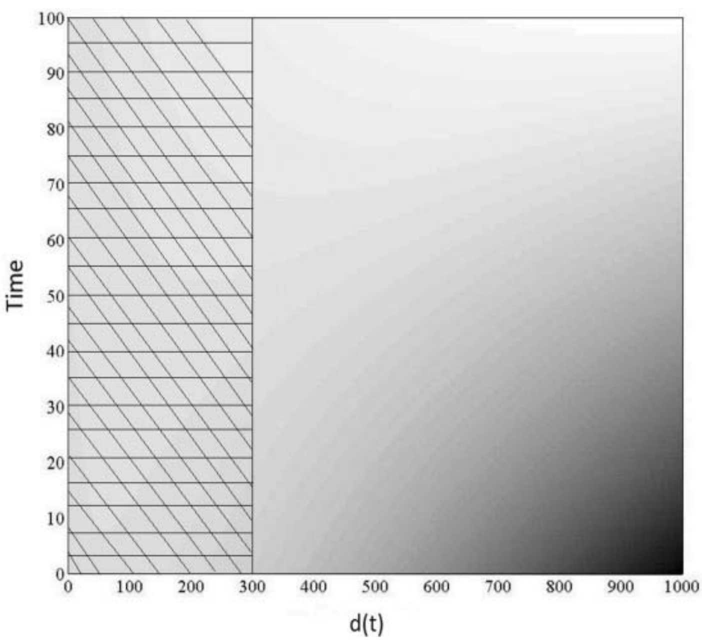

Figure B.2. Land-use revenues (view from top).

regime. The solution for the optimal deforestation path is given by

$$d(t) = \begin{cases} d(0)e^{rt} + \dfrac{P^{cc}(0)(e^{\delta t} - e^{rt}) - a_1(1 - e^{rt}) - P^R(0)(e^{\gamma t} - e^{rt})}{2a_2}, & \text{if } t \in [0, \tau) \\ d(\tau)e^{rt} + \dfrac{P^{cc}(\tau)(e^{\delta t} - e^{rt}) - a_1(1 - e^{rt})}{2a_2}, & \text{if } t \in [\tau, T] \end{cases} \tag{B.4}$$

Considering the lack of continuity at τ, we solve the landowner's maximisation using a numerical search algorithm that combines all possible combinations of Regime 1 and Regime 2 paths at different switching points.[31] We select the combined path that yields the highest profits.

In the case of the corridor scenarios, the profit function is non-smooth at two points, i.e. at the boundaries of the corridor (dB^U and dB^L for the fixed; dB^U and dB^L for the variable); the landowner will be able to switch between three different regimes. Depending on the relationship between initial parameter values, they will choose an optimal deforested area that satisfies

$$d(t) = \begin{cases} d(0)e^{rt} + \dfrac{P^{cc}(0)(e^{\delta t} -, e^{rt}) - a_1(1 - e^{rt}) - P^R(0)(e^{\gamma t} -, e^{rt})}{2a_2}, & \text{if } t \in [0, \tau_1) \\ d(\tau_1)e^{rt}\dfrac{a_2 - \dfrac{P^R(\tau_1)}{dB^U - dB^L}}{a_2 - \dfrac{P^R(\tau_1)e^{\gamma t}}{dB^U - dB^L}} + \dfrac{P^{cc}(\tau_1)(e^{\delta t} -, e^{rt}) - a_1(1 -, e^{rt}) - P^R(\tau_1)(e^{\gamma t} -, e^{rt})\left(1 + \dfrac{dB^U + dB^L}{dB^U - dB^L}\right)}{2\left(a_2 - \dfrac{P^R(\tau_1)e^{\gamma t}}{dB^U - dB^L}\right)}, & \text{if } t \in [\tau_1, \tau_2) \\ d(\tau_2)e^{rt} + \dfrac{P^{cc}(\tau_2)(e^{\delta t} -, e^{rt}) - a_1(1 - e^{rt})}{2a_2}, & \text{if } t \in [\tau_2, T] \end{cases} \tag{B.5}$$

in the fixed-corridor case. For the variable corridor, the optimal deforestation rate will take the same form, with $dB^U(t)$ and $dB^L(t)$ replacing dB^U and dB^L, respectively. In our setting, the order of the switching times ($0 \leq \tau_1 \leq \tau_2 \leq T$) is due to the combination of two characteristics of our model. First, the benefits of taking part in REDD decrease over time: for later periods, net revenues from land exploitation outpace REDD revenues due to higher composite commodity prices and larger deforestation rates. Second, REDD gains get marginally smaller as the deforestation level gets closer to the upper corridor boundary until it eventually fades away for rates above the corridor. Therefore, the motivation to stay in REDD decreases over time, but at different paces within each

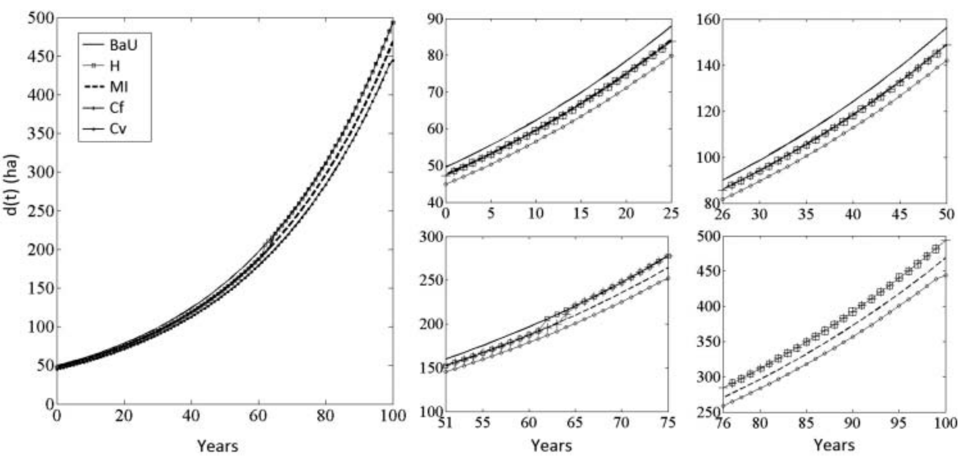

Figure B.3. Optimal deforestation paths under BaU and different REDD baselines, detailed for sub-periods of 25 years.

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interval. The landowner's optimisation problem accounts for three possible regimes:

$$\max_{d(t)|t\in[0,T]}\left\{\int_0^{\tau_1} e^{-rt},\pi^{R_1}\left(d(t)\right)dt+\int_{\tau_1}^{\tau_2},e^{-rt},\pi^{R_2}\left(d(t)\right)dt+\int_{\tau_2}^{T},e^{-rt},\pi^{R_3}\left(d(t)\right)dt\right\} \tag{B.5}$$

To determine the optimal regime switching times (τ_1 and τ_2), we first define optimal paths within each regime for all possible combinations of switching times. We then use a numerical search algorithm that selects the combination of the three paths yielding the highest profits.

Figure B.3 captures the optimal deforestation path for the BaU and the four REDD baseline methodologies. The large box on the left-hand side refers to the entire deforestation path, reproducing the results in Figure 1. To better understand the differences in optimal deforestation for each baseline, we detail in the other boxes on the right-hand side the deforestation path for sub-periods of 25 years each.

C. Efficiency of the single-threshold and corridor approaches

Proposition: The single-threshold baseline approach is more efficient than the corresponding corridor approach, that is,

$$E_3^{\mathrm{H}}\leq E_3^{\mathrm{Cf}} \tag{C.1}$$

$$E_3^{\mathrm{MI}}\leq E_3^{\mathrm{Cv}} \tag{C.2}$$

where $E_3^i=\frac{SRR^i}{S_{\mathrm{Tot}}^{\mathrm{BaU}}-S_{\mathrm{Tot}}^i}$, where $SRR^i=\int^T{}_0 RR^i(t)dt$, $S^i{}_{\mathrm{Tot}}=\int_0{}^T d^i(t)dt$, $i\in\{\mathrm{H, MI, Cf, Cv}\}$, and BaU stands for business-as-usual.

Proof: Let *ST* refer to the single-threshold approach and *C* to the corresponding corridor approach. For the proof, we will use three results from Section 3.1. First, relations (15) and (16) in Section 3.1 show that

$$RR^{ST}(t)\leq RR^{C}(t) \tag{C.3}$$

Since relation (C.3) holds $\forall t\in[0;T]$, we can write that

$$\int_0^T RR^{ST}(t)dt\leq\int_0^T RR^{C}(t)dt\Leftrightarrow SRR^{ST}\leq SRR^{C} \tag{C.4}$$

Let us denote then

$$SRR^{ST}=(1-a)SRR^{C} \tag{C.5}$$

with $a\in[0;1]$ such that relation (C.5) is satisfied.

Second, relations (17) and (18) in Section 3.1 show that

$$E_1^{ST}\leq E_1^{C} \tag{C.6}$$

From the definition of $E^i{}_1$, it follows that

$$\frac{S_{\mathrm{Tot}}^{\mathrm{BaU}}-S_{\mathrm{Tot}}^{ST}}{S_{\mathrm{Tot}}^{\mathrm{BaU}}}\leq\frac{S_{\mathrm{Tot}}^{\mathrm{BaU}}-S_{\mathrm{Tot}}^{C}}{S_{\mathrm{Tot}}^{\mathrm{BaU}}}\Leftrightarrow S_{\mathrm{Tot}}^{\mathrm{BaU}}-S_{\mathrm{Tot}}^{ST}\leq S_{\mathrm{Tot}}^{\mathrm{BaU}}-S_{\mathrm{Tot}}^{C} \tag{C.7}$$

Let us denote then

$$S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{ST} = (1-b)\left(S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{C}\right) \tag{C.8}$$

where $b \in [0; 1]$ such that relation (C.7) is satisfied.

Third, we observe from Table 4 that $a > b$, i.e. the percentage gain in welfare (a) achieved by the corridor relative to the single-threshold approach is larger than its gain in effectiveness (b). Therefore, accounting for relations (C.5) and (C.8), we can compare the efficiency of the single-threshold and corridor approaches:

$$E_3^{ST} - E_3^{C} = \frac{SRR^{ST}}{S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{ST}} - \frac{SRR^{C}}{S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{C}} = \frac{(1-a)SRR^{C}}{(1-b)(S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{C})} - \frac{SRR^{C}}{S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{C}} \tag{C.9}$$

$$E_3^{ST} - E_3^{C} = \frac{SRR^{C}}{S_{\mathrm{Tot}}^{\mathrm{BaU}} - S_{\mathrm{Tot}}^{C}}\,\frac{b-a}{1-b} \tag{C.10}$$

With $a > b$, we get that

$$E_3^{ST} \leq E_3^{C} \tag{C.11}$$

D. Parameter calibration and sensitivity analysis

This section verifies the robustness of our results to several key calibration parameters, namely the carbon content of the forest, the discount rate, and the growth rates of the composite commodity and REDD permit prices.

D1. Forest carbon content (Ω)

REDD programmes aim to achieve reductions in emissions from deforestation below BaU levels. While deforestation can be measured in terms of hectares of land where forest has been removed, the GHG emissions coming from deforestation depend on the carbon content stored in the trees. The carbon content of one hectare of forest can vary across geographical regions, depending on tree type and forest density.

Across the REDD candidate countries, the average carbon content varies widely. Figure D.1 captures the distribution of the average above and below ground carbon content of 85 REDD countries, grouped according to their deforestation patterns and the geographical region.[32] The variability of the carbon content is very large even within each geographical and forest transition theory (FTT) group.

The forest carbon content varies not only from country to country, but also within countries. Figure D.3 shows the above ground carbon content across the territory of Peru,[33] which takes values from 0 to more than 150 tC/ha. The existence of large differences between the carbon content of different regions brings a strong argument for the need to design REDD projects that take into account regional characteristics.

The success of REDD is likely to depend on its ability to provide payments that correctly reflect the carbon content of each project area. We test the sensitivity of the baseline performance to different levels of carbon content per hectare of forest. This setting depicts a situation where REDD projects are implemented in several regions of a country, with the average carbon content varying from region to region. Holding everything else constant, we assume identical conditions regarding the composite commodity and REDD permit markets across the different regions.

Figure D.2 illustrates the performance of the four REDD baselines across different levels of average carbon content. It demonstrates the robustness of the baseline ranking presented in

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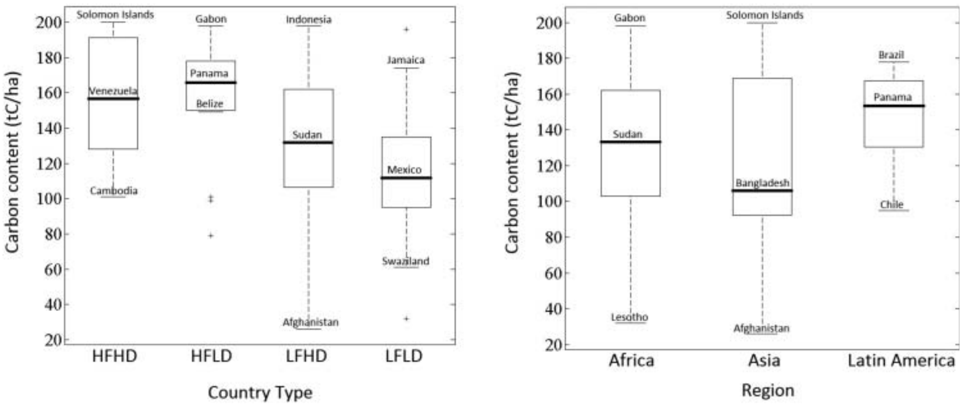

Figure D.1. Distributions of the average above and below ground carbon contents across different stages of FTT and world regions.
Notes: The right-hand panel groups countries according to the geographical region. The left-hand panel groups countries based on their deforestation patterns according to the FTT. HFHD is high forest, high deforestation; HFLD is high forest, low deforestation; LFHD is low forest, high deforestation; LFLD is low forest, low deforestation. *Source*: Authors' own calculations based on OSIRIS v.3-4.

Section 3.1. The variable corridor (Cv) continues to be the most effective in reducing deforestation. The fixed corridor (Cf) offers the highest increase in welfare from BaU. The model-implied baseline (MI) is the most efficient, having the lowest costs per hectare of avoided deforestation.

Additionally, we observe an increase in the difference in performance of the static versus dynamic baselines at higher carbon contents. The results are particularly interesting in terms of effectiveness; it results that REDD projects employing the variable-corridor (Cv) approach will have a high potential in reducing deforestation and the inherent GHG emissions, especially if they target high carbon content (HCC) areas. With the current international fora inclined to direct REDD programmes towards HCC areas, it appears especially important to understand and underline the benefits of the variable-corridor approach.

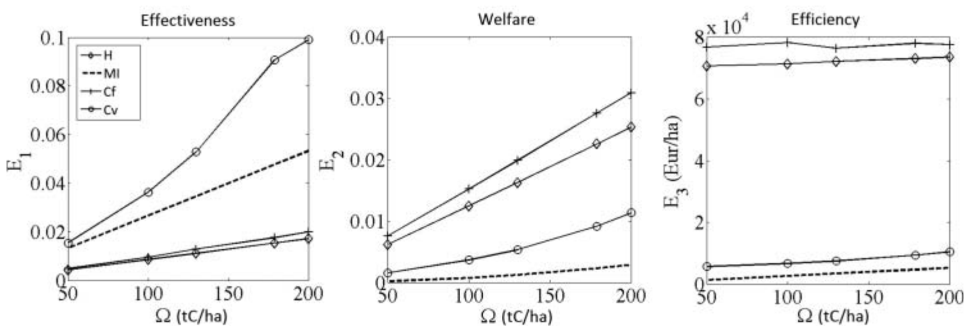

Figure D.2. Baseline performance across different average forest carbon contents (Ω).
Notes: The figure captures the performance of the four baselines for different average carbon contents per hectare of forest. The historical deforestation rate (dB) is 200 ha/year. Corridor width is $x = 0.1$.

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*D2. Crediting threshold in the static baselines (*dB*)*

In this section, we verify the change in the performance of the static baseline approaches to different crediting levels. The REDD rewards of the historical and fixed-corridor approaches depend on the fixed threshold *dB* (Table 5). As mentioned in the baseline presentation (Section 2.2), the fixed threshold can be set equal to the average past deforestation in the area. Aside from data availability and estimation issues, linking rewards to a single value over a larger horizon can result in payments

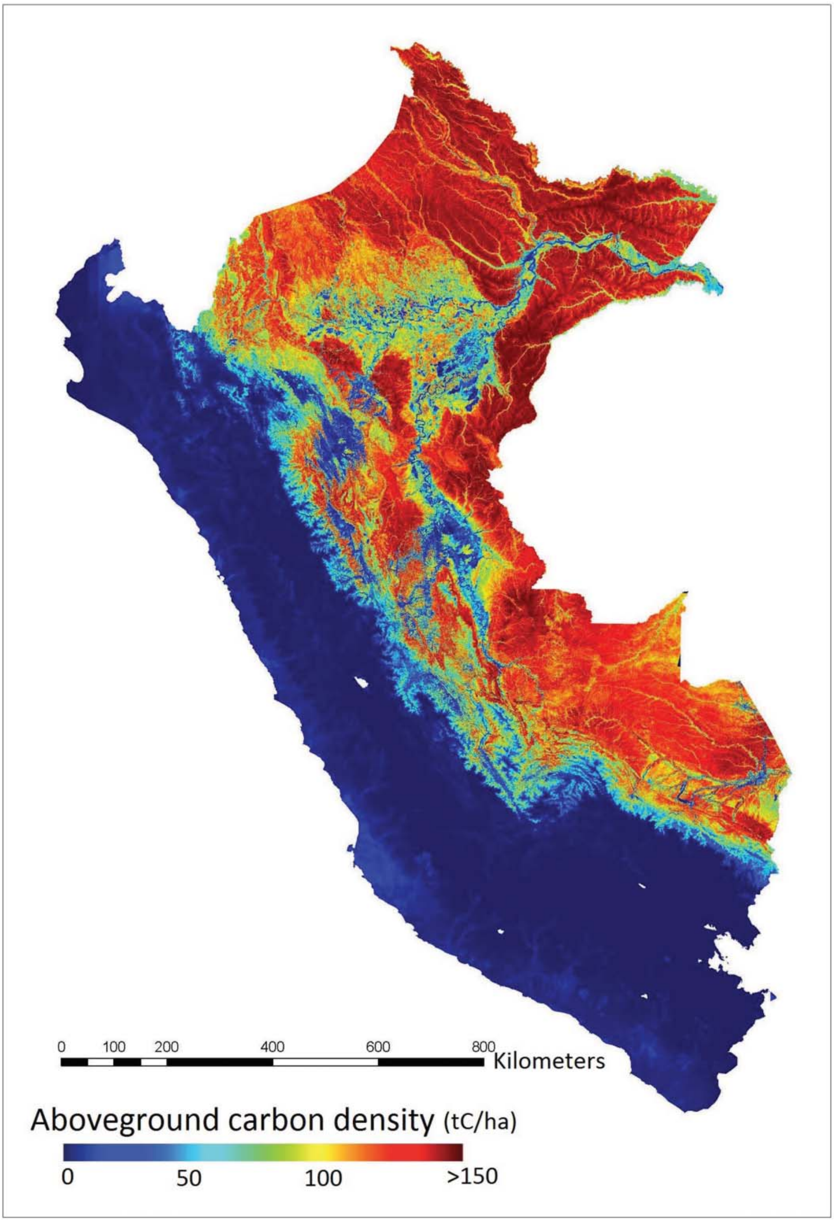

Figure D.3. Above ground carbon content in Peru.
Source: *The High-resolution Carbon Geography of Peru*, Carnegie Institution for Science, 2014, available online at http://carnegiescience.edu/news/per%C3%BA%E2%80%99s_carbon_quantified_economic_and_conservation_boon.

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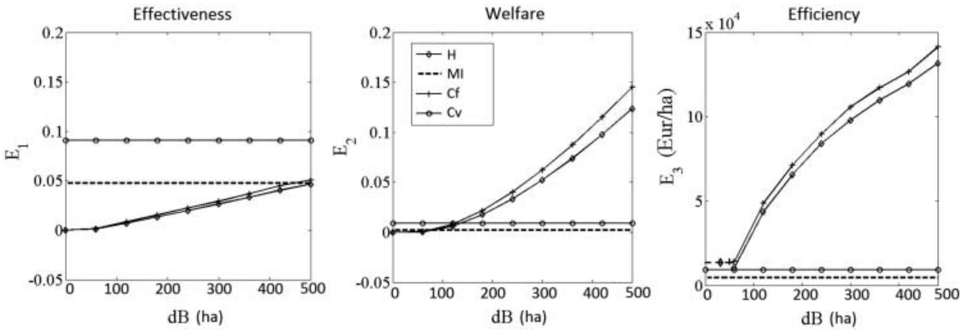

Figure D.4. Baseline performance across different fixed thresholds.
Notes: The ranking of the four baselines changes across different historical deforestation rates. For the historical and fixed-corridor baselines, efficiency is not defined for deforestation averages below 60 ha/year, where deforestation reduction and REDD costs are zero. Corridor width is $x = x_0 = 0.1$.

that reflect only partially actual efforts. There remains a certain level of risk involved in choosing a fixed threshold, and we check now the sensitivity of baseline performance to various levels (*dB*) against which rewards are accrued for the historical and fixed-corridor schemes. The results are displayed in Figure D.4. We find that the ranking of baselines is robust to variations in the fixed threshold level *dB*. The historical and the fixed-corridor baselines gain ground at larger fixed thresholds, in terms of both effectiveness and welfare. However, these improvements come at the high cost of large losses in efficiency.

The increase in welfare at higher *dB* follows from the fact that the REDD revenues of the historical and fixed-corridor schemes are an increasing function of the fixed threshold. This is confirmed by the positive partial derivatives of the REDD revenue functions of the static baselines with respect to *dB*. Moreover, the higher REDD revenues foster increases in effectiveness, but also reductions in efficiency.

Our findings show that, if a static baseline is selected, the fixed threshold should be set above the average predicted deforestation rate in order to achieve stronger effectiveness and welfare results.

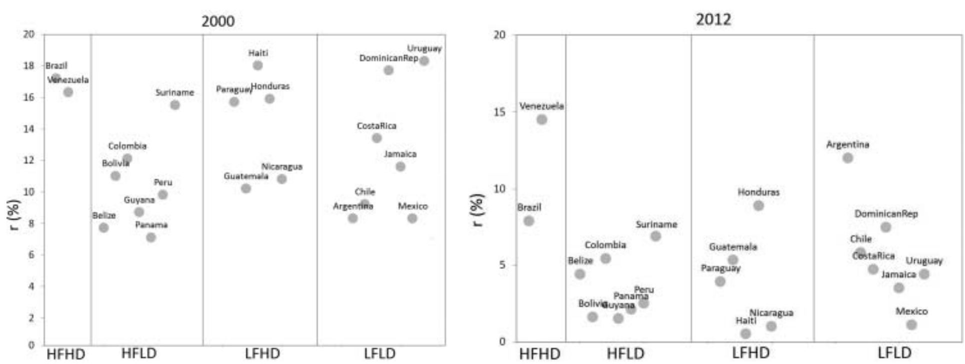

Figure D.5. Deposit rates (r) in the Latin America region in the years 2000 and 2012.
Source: Authors' own graphical representation based on the data provided by the World Bank, World Development Indicators, available online at http://wdi.worldbank.org/table/4.15.

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D3. Discount rate (r)

In our initial calibration, the discount rate was chosen slightly below the growth rates of the composite commodity and REDD permit prices, depicting a setting in which forest exploitation and REDD bring higher financial benefits than saving at the discount rate. However, the discount rate in many developing countries varies widely from country to country and across time. Figure D.5 shows the discount rates for the years 2000 and 2012 in the Latin America region, with r taking values in the range [0.5%, 19.5%].

We test the sensitivity of our results to changes in the discount rate. Figure D.6 shows the total deforested area under BaU and the four REDD baseline methodologies. The BaU optimal deforestation rate is a decreasing function in r (Equation (A.11)), with higher impacts at later periods of time (as t approaches T). We detail the impact on the static and the dynamic baselines separately:

- Higher discount rates reduce the total deforestation of the static baselines. The landowner switches from REDD to BaU in the second part of the optimisation horizon (see Figure D.7). After the switch, the optimal deforestation follows the BaU path, achieving reductions in deforestation due to higher r.
- For the prospective baselines, whose reference levels depend on the BaU deforestation ($dB(t) = d_{\mathrm{BaU}}(t)$), the impact of an increase in r on total deforestation is non-monotonous. The plots of total deforestation at different r present an inflection point (at $r = 8\%$ for MI and $r = 2\%$ for Cv). For r lower than the inflection point, an increase in r leads to a decrease in total deforestation; for r higher than the inflection point, an increase in r leads to higher deforestation. Below the inflection point, an increase in r results in lower $dB(t)$, requiring stronger reductions in deforestation for obtaining the same REDD profits. Reducing the deforestation rate pays off until some point (the inflection point), above which the time-varying threshold is so low that the opportunity costs of REDD exceed the benefits, and the landowner is better off following the BaU scenario (exiting REDD and increasing deforestation) (see Figure D.7).

Figure D.8 shows that the ranking of baselines across the three performance measures is robust across different discount rates. Additionally, for higher discount rates, the difference in

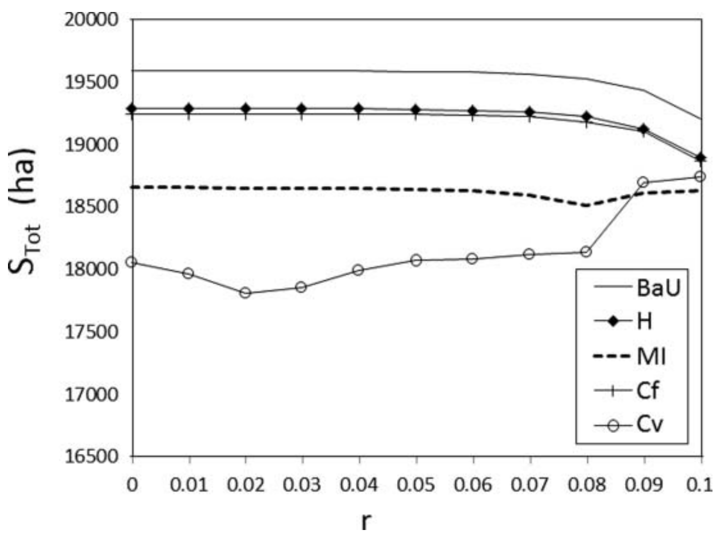

Figure D.6. Total deforestation across different baselines and discount rates (r).

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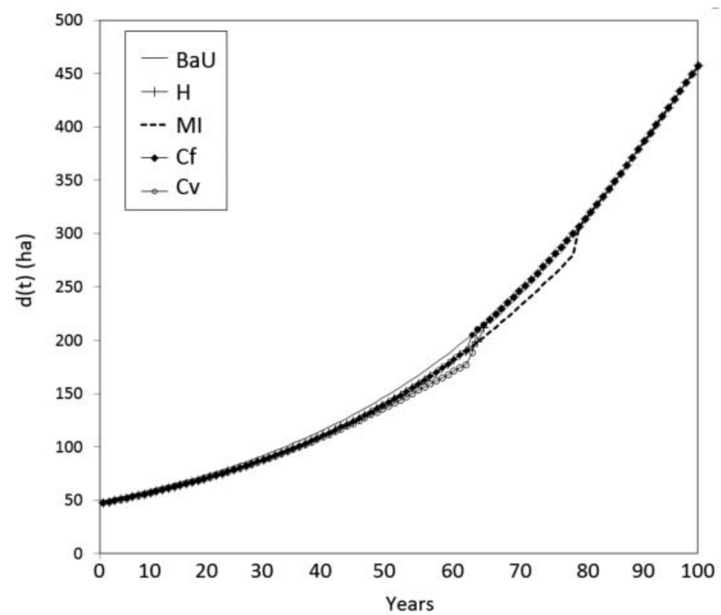

Figure D.7. Optimal deforestation across different baselines ($r = 0.1$).

performance between the static and dynamic baselines decreases in terms of effectiveness and efficiency, but widens considerably in terms of welfare. The results need to be interpreted carefully. Firstly, at higher r, both BaU and static baselines result in lower total welfare. The impact of higher r on the change in welfare from BaU is measured by the E_2 indicator. With the income under the static baselines decreasing less than the BaU income, the percentage change in welfare appears to be increasing, despite the fact that welfare itself is decreasing in r.

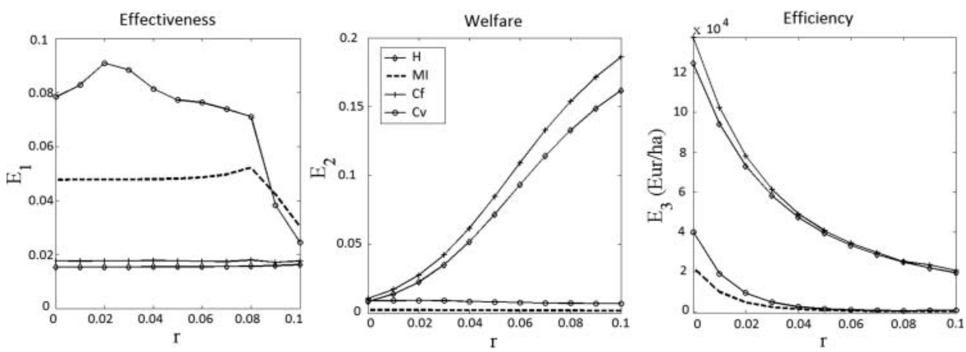

Figure D.8. Baseline performance across different discount rates (r).
Notes: The figure captures the performance of the four baselines for different discount rates. The historical deforestation rate (dB) is at 200 ha/year. Corridor width is $x = 0.1$.

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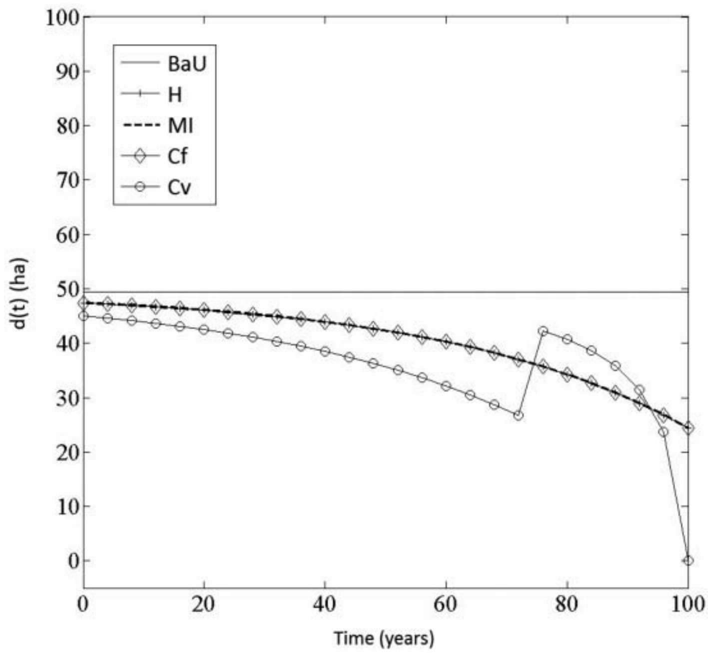

Figure D.9. Optimal deforestation across different baselines ($\delta = 0$).

Second, with efficiency measured as total discounted REDD revenues per hectares of avoided deforestation (the E_3 indicator), an increase in r reduces heavily the nominator (lower total discounted revenues), without increasing the forest area saved (we have seen that effectiveness is constant across different r). The improvement in efficiency at higher r is, therefore, just a discounting effect.

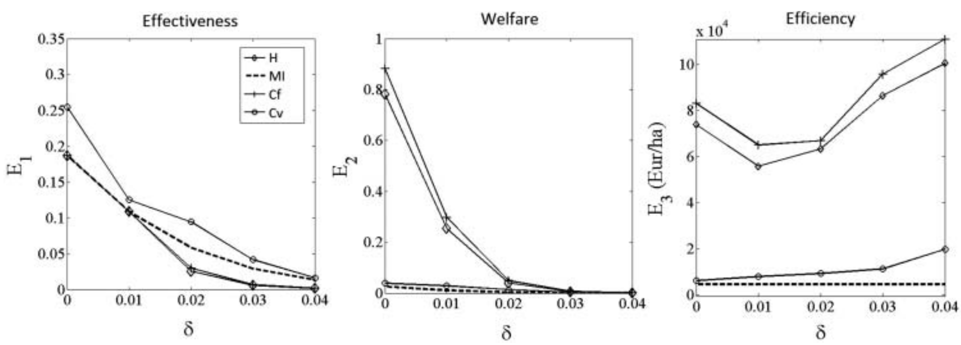

Figure D.10. Baseline performance across different growth rates of the composite commodity price (δ).
Notes: The figure captures the performance of the four baselines for different growth rates of the composite commodity price. The historical deforestation rate (dB) is at 200 ha/year. Corridor width is $x = 0.1$.

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Summing up, we find that the ranking of baselines at different discount rates is consistent with the results presented under the initial calibration (Section 3.1). Higher discount rates lower the amount of total deforestation, especially for periods of time that are further away in the future. With lower deforestation also under BaU, there is little room for additionality obtained by REDD, and the effectiveness of the different baselines decreases. We argue that policy-makers interested in achieving high effectiveness might prefer to direct REDD projects to countries of higher political stability, where discount rates are lower.

D4. Growth rate of the composite commodity price (δ)

REDD programmes are currently being designed in many developing countries, and the opportunity costs of avoiding deforestation are likely to vary widely across different regions. The price dynamics of the alternative land use – in our model the growth rate of the composite commodity price (δ) – represents a key parameter influencing the opportunity costs of avoiding deforestation. Intuitively, the higher the growth rate of the composite commodity, the larger the price of the commodity in the future, strengthening the incentives to deforest more at later periods of time. With higher opportunity costs, REDD programmes are expected to be less effective (Irawan et al. 2013).

Figure D.9 shows that when the growth rate of the price of the agricultural composite commodity is low ($\delta = 0$), the deforestation path will be decreasing in time, since the REDD permit price increases and makes REDD participation more attractive. With constant, although different, baselines, the historical, model-implied, and fixed corridors lead to the same deforestation path. With constant agricultural composite commodity prices, it is the variable corridor that achieves again the best results in terms of avoided emissions. Although the H, MI, and Cf baselines obtain the same levels of effectiveness, they differ significantly in terms of welfare change and efficiency (see Figure D.10).

We test the sensitivity of baseline ranking to different levels of opportunity costs, by varying the growth rate of the composite commodity. We observe that, with our calibration, for $\delta > 0.04$ REDD projects are no longer effective in reducing deforestation below BaU.

Figure D.10 shows that the ranking of baselines is consistent with the results presented in Section 3.1 across all values of δ. Higher values of δ increase deforestation under BaU and the four REDD scenarios, reducing the effectiveness of REDD, as expected. As δ gets higher, landowners opt out of REDD and follow BaU, with their welfare converging to the BaU income. At lower effectiveness rates, payments for deforestation reductions under REDD are less cost-efficient.

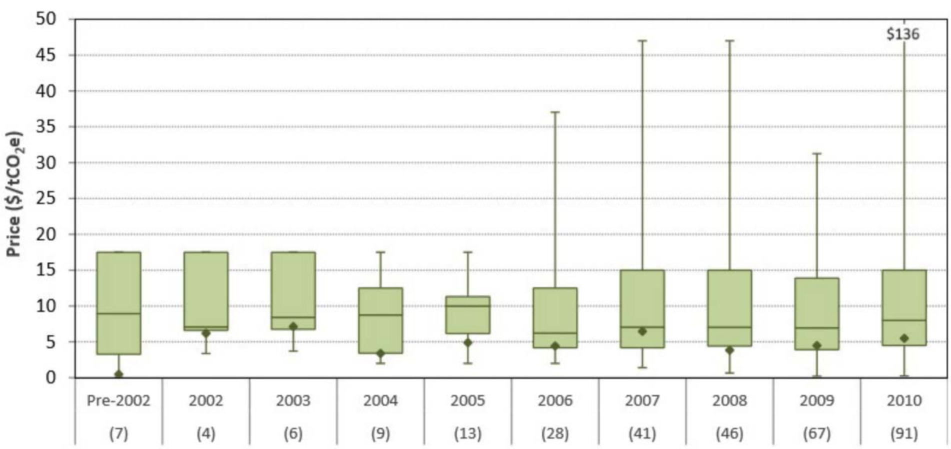

Figure D.11. Historical forest carbon price distributions (primary market).
Source: Diaz et al. (2011), *Ecosystem Marketplace*, available online at http://www.forest-trends.org/documents/files/doc_2963.pdf. Values in parentheses show the number of reported prices included in each year.

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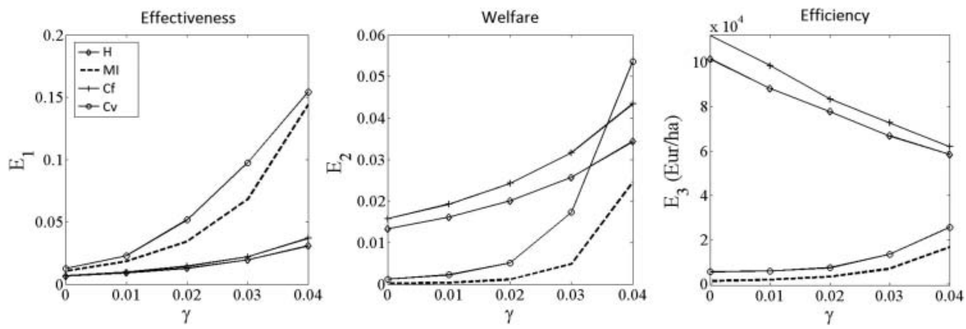

Figure D.12. Baseline performance across different growth rates of the REDD permit (γ).
Notes: The figure captures the performance of the four baselines for different growth rates of the REDD permit price. The historical deforestation rate (dB) is at 200 ha/year. Corridor width is $x = 0.1$.

The policy implication that arises from our analysis is that REDD programmes need to be accompanied by payments that stand up to the specific opportunity costs of the region; otherwise, where opportunity costs are very high, REDD programmes will be ineffective. This result is in line with the of findings of Irawan et al. (2013), who underline that REDD might not be able to compete with some alternative land uses that have prohibitive opportunity costs.

D5. Growth rate of the REDD permit price (γ)

The success of REDD is critically dependent on the incentive structure offered by the scheme. A key element is the amount of money rewarded per hectare of avoided deforestation, given by the REDD permit price (P^R) and its growth rate over time (γ).

Forest carbon projects have started their slow but steady increase at the end of the 1980s, and since then the largest part of demand for forest offsets has come from the voluntary carbon markets. Since 2005, forest carbon markets have experienced a significant boom, clearly marked by the development of REDD projects starting with 2010 (Diaz et al. 2011). REDD projects do not result in unique prices per ton of avoided emissions from deforestation; instead, prices vary according to demand levels, international regulations, and the quality of the specific projects.[34] Figure D.11 captures the historical distribution of forest carbon prices and illustrates two key characteristics of the market: (1) forest carbon prices present large variability; and (2) the trend in average prices after 2008 was increasing.

Motivated by the high price variability observed empirically, and by the fact that only increasing prices can motivate the sustained reduction of deforestation in the long run, we test the robustness of our results to different growth rates of the REDD credits price (γ).

Figure D.12 captures the performance of the four REDD baseline methodologies across different levels of γ. The baseline ranking presented in Section 3.1 is robust to changes in the growth rate of the REDD price. As expected, low future REDD prices diminish the incentives to avoid deforestation, and the modest reductions in deforestation are cost-inefficient. In contrast, if forest owners expect large future increases in REDD prices, they are motivated to keep the deforestation rates significantly lower than the BaU scenario; REDD projects are in this case likely to achieve high effectiveness. Moreover, the higher is the growth rate, the larger becomes the difference in effectiveness between the static and the dynamic baselines.

The policy implication that results from our analysis is that it is not enough to ensure high future REDD payments in order to achieve large reductions in deforestation, but it is necessary to choose carefully the baseline methodology. While static baselines achieve limited effectiveness at high REDD rewards, a dynamic baseline approach, designed as a corridor around the estimated BaU deforestation rate, will strongly increase the effectiveness of REDD.

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E Corridor bandwidth and symmetry

E1. Fixed corridor

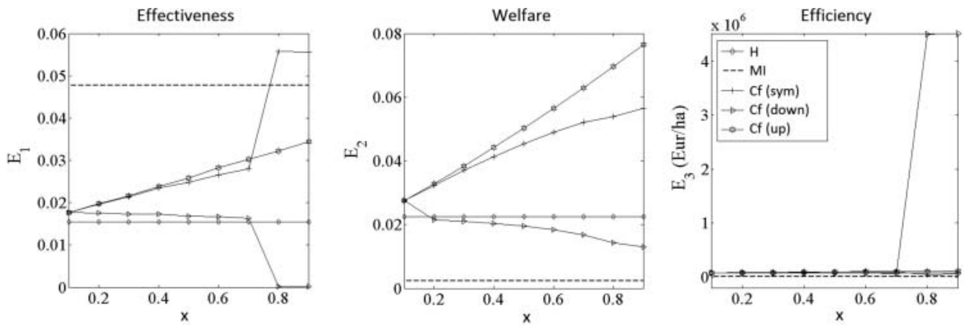

Figure E.1. Performance of the fixed corridor at different corridor bandwidths (x).
Notes: The figure captures the performance of the fixed corridor for different corridor widths and symmetry assumptions. Considered corridors are symmetric (*sym*), upward (*up*), and downward biased (*down*). Bounds in the downward-biased case are set as $dB^U = (1 + x_0)dB$, $dB^L = (1 - x)dB$; in the upward-biased case, $dB^U = (1 + x)dB$, $dB^L = (1 - x_0)dB$, with $x \in [0.1, 0.9]$ and $x_0 = 0.1$

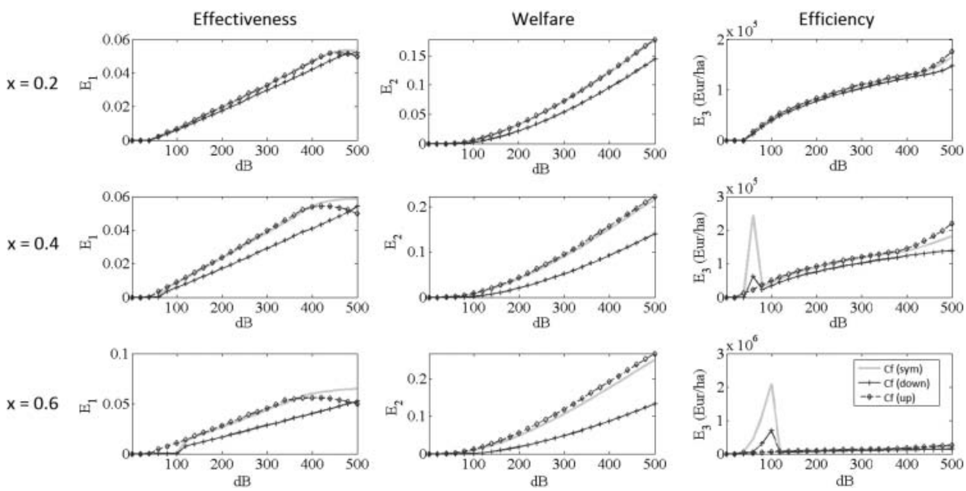

Figure E.2. Performance of the fixed corridor at different fixed thresholds (dB).
Notes: The figure captures performance results of the fixed (symmetric, upward, and downward biased) corridor. Three cases of corridor width are considered ($x \in \{0.2, 0.4, 0.6\}$) for different fixed thresholds ($dB \in [1, 500]$ ha/year).

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Table E.1 REDD revenues detailed for different ranges of the deforestation rate.

Deforestation range	Symmetric	Upward biased	Downward biased	Ranking
Cf	$RR(t) = P^R(t)\left(1 - \frac{(d(t)-dB^L)^+}{dB^U-dB^L}\right)\left(dB^U - d(t)\right)^+$			
$d(t) \in [0, (1-x)dB]$	$P^R(t)((1+x)dB - d(t))$	$P^R(t)((1+x)dB - d(t))$	$P^R(t)((1+x_0)dB - d(t))$	$RR(t)^{up} = RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \in ((1-x)dB, (1-x_0)dB]$	$P^R(t)\frac{((1+x)dB-d(t))^2}{2xdB}$	$P^R(t)((1+x)dB - d(t))$	$P^R(t)\frac{((1+x_0)dB-d(t))^2}{(x+x_0)dB}$	$RR(t)^{up} \geq RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \in ((1-x_0)dB, (1+x_0)dB]$	$P^R(t)\frac{((1+x)dB-d(t))^2}{2xdB}$	$P^R(t)\frac{((1+x)dB-d(t))^2}{(x+x_0)dB}$	$P^R(t)\frac{((1+x_0)dB-d(t))^2}{(x+x_0)dB}$	$RR(t)^{up} \geq RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \in ((1+x_0)dB, (1+x)dB]$	$P^R(t)\frac{((1+x)dB-d(t))^2}{2xdB}$	$P^R(t)\frac{((1+x)dB-d(t))^2}{(x+x_0)dB}$	0	$RR(t)^{up} \geq RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \geq (1+x)dB$	0	0	0	$RR(t)^{up} = RR(t)^{sym} = RR(t)^{down}$
Cv	$RR(t) = P^R(t)\left(1 - \frac{(d(t)-dB^L(t))^+}{dB^U(t)-dB^L(t)}\right)(dB^U(t) - d(t))^+$			
$d(t) \in [0, (1-x)dB(t)]$	$P^R(t)((1+x)dB(t) - d(t))$	$P^R(t)((1+x)dB(t) - d(t))$	$P^R(t)((1+x_0)dB(t) - d(t))$	$RR(t)^{up} = RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \in ((1-x)dB(t), (1-x_0)dB(t)]$	$P^R(t)\frac{((1+x)dB(t)-d(t))^2}{2xdB(t)}$	$P^R(t)((1+x)dB(t) - d(t))$	$P^R(t)\frac{((1+x_0)dB(t)-d(t))^2}{(x+x_0)dB(t)}$	$RR(t)^{up} \geq RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \in ((1-x_0)dB(t), (1+x_0)dB(t)]$	$P^R(t)\frac{((1+x)dB(t)-d(t))^2}{2xdB(t)}$	$P^R(t)\frac{((1+x)dB(t)-d(t))^2}{(x+x_0)dB(t)}$	$P^R(t)\frac{((1+x_0)dB(t)-d(t))^2}{(x+x_0)dB(t)}$	$RR(t)^{up} \geq RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \in ((1+x_0)dB(t), (1+x)dB(t)]$	$P^R(t)\frac{((1+x)dB(t)-d(t))^2}{2xdB(t)}$	$P^R(t)\frac{((1+x)dB(t)-d(t))^2}{(x+x_0)dB(t)}$	0	$RR(t)^{up} \geq RR(t)^{sym} \geq RR(t)^{down}$
$d(t) \geq (1+x)dB(t)$	0	0	0	$RR(t)^{up} = RR(t)^{sym} = RR(t)^{down}$

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Table E.2 Change in REDD revenues when varying corridor bandwidth and deforestation rate.

Symmetry	Boundaries	$\frac{\partial RR(t)}{\partial x}$	$\frac{\partial RR(t)}{\partial x}$	$\frac{\partial^2 RR(t)}{\partial x \partial d(t)}$	$\frac{\partial^2 RR(t)}{\partial x \partial d(t)}$
Cf		$d(t) \in [0, dB^L]$	$d(t) \in (dB^L, dB^U)$	$d(t) \in [0, dB^L]$	$d(t) \in (dB^L, dB^U)$
Symmetric	$dB^L = (1-x)dB$ $dB^U = (1+x)dB$	$P^R(t)dB > 0$	$P^R(t)\frac{((1+x)dB-d(t))((x-1)dB+d(t))}{2x^2 dB} > 0$	0	$P^R(t)\frac{dB-d(t)}{x^2 dB} > 0$ $(\forall d(t) \in (dB^L, dB])$
Upward biased	$dB^L = (1-x_0)dB$ $dB^U = (1+x)dB$	$P^R(t)dB > 0$	$P^R(t)\frac{((1+x)dB-d(t))((x+2x_0-1)dB+d(t))}{(x_0+x)^2 dB} > 0$	0	$2P^R(t)\frac{(1-x_0)dB-d(t)}{(x_0+x)^2 dB} < 0$
Downward biased	$dB^L = (1-x)dB$ $dB^U = (1+x_0)dB$	0	$-P^R(t)\frac{((1+x_0)dB-d(t))^2}{(x_0+x)^2 dB} < 0$	0	$2P^R(t)\frac{(1+x_0)dB-d(t)}{(x_0+x)^2 dB} > 0$
Cv		$d(t) \in [0, dB^L(t)]$	$d(t) \in (dB^L(t), dB^U(t))$	$d(t) \in [0, dB^L(t)]$	$d(t) \in (dB^L(t), dB^U(t))$
Symmetric	$dB^L(t) = (1-x)dB(t)$ $dB^U(t) = (1+x)dB(t)$	$P^R(t)dB(t) > 0$	$P^R(t)\frac{((1+x)dB(t)-d(t))((x-1)dB(t)+d(t))}{2x^2 dB(t)} > 0$	0	$P^R(t)\frac{dB(t)-d(t)}{x^2 dB(t)} > 0$ $(\forall d(t) \in (dB^L(t), dB(t)])$
Upward biased	$dB^L(t) = (1-x_0)dB(t)$ $dB^U(t) = (1+x)dB(t)$	$P^R(t)dB(t) > 0$	$P^R(t)\frac{((1+x)dB(t)-d(t))((x+2x_0-1)dB(t)+d(t))}{(x_0+x)^2 dB(t)} > 0$	0	$2P^R(t)\frac{(1-x_0)dB(t)-d(t)}{(x_0+x)^2 dB(t)} < 0$
Downward biased	$dB^L(t) = (1-x)dB(t)$ $dB^U(t) = (1+x_0)dB(t)$	0	$-P^R(t)\frac{((1+x_0)dB(t)-d(t))^2}{(x_0+x)^2 dB(t)} < 0$	0	$2P^R(t)\frac{(1+x_0)dB(t)-d(t)}{(x_0+x)^2 dB(t)} > 0$

Notes: Columns (3) and (4) show results for first partial derivatives of REDD revenues with respect to corridor width across different symmetry scenarios for the fixed- and the variable-corridor methodologies. Columns (5) and (6) display results of the second partial derivative of REDD revenues, first with respect to corridor width and then with respect to deforestation rate. A distinction is made between the case when the deforestation rate is below the lower boundary and the case when it is inside the corridor.

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Table E.3 Double impact of varying the corridor width on REDD revenues.

Symmetry	Characteristics	Linear impact on REDD credits (n)	Non-linear impact on weight (ω)
Cf			
Symmetric	$dB^L = (1-x)dB$	$\frac{\partial n}{\partial x} = dB > 0$	$\frac{\partial \omega}{\partial x} = \frac{d(t) - dB}{2x^2 dB}$
	$dB^U = (1+x)dB$		$(\frac{\partial \omega}{\partial x} < 0$ if $d(t) < dB)$
	$n = (1+x)dB - d(t)$		$(\frac{\partial \omega}{\partial x} \geq 0$ if $d(t) \geq dB)$
	$\omega = 1 - \frac{d(t)-(1-x)dB}{(1+x)dB-(1-x)dB}$		
Upward biased	$dB^L = (1-x_0)dB$	$\frac{\partial n}{\partial x} = dB > 0$	$\frac{\partial \omega}{\partial x} = \frac{d(t)-(1-x_0)dB}{(x+x_0)^2 dB} > 0$
	$dB^U = (1+x)dB$		
	$n = (1+x)dB - d(t)$		
	$\omega = 1 - \frac{d(t)-(1-x_0)dB}{(1+x)dB-(1-x_0)dB}$		
Downward biased	$dB^L = (1-x)dB$	$\frac{\partial n}{\partial x} = 0$	$\frac{\partial \omega}{\partial x} = \frac{d(t)-(1+x_0)dB}{(x+x_0)^2 dB} < 0$
	$dB^U = (1+x_0)dB$		
	$n = (1+x_0)dB - d(t)$		
	$\omega = 1 - \frac{d(t)-(1-x)dB}{(1+x_0)dB-(1-x)dB}$		
Cv			
Symmetric	$dB^L(t) = (1-x)dB(t)$	$\frac{\partial n}{\partial x} = dB(t) > 0$	$\frac{\partial \omega(t)}{\partial x} = \frac{d(t)-dB(t)}{2x^2 dB(t)} < 0$
	$dB^U(t) = (1+x)dB(t)$		(since optimal $d(t) < dB(t)$)
	$n = (1+x)dB(t) - d(t)$		
	$\omega(t) = 1 - \frac{d(t)-(1-x)dB(t)}{(1+x)dB(t)-(1-x)dB(t)}$		
Upward biased	$dB^L(t) = (1-x_0)dB(t)$	$\frac{\partial n}{\partial x} = dB(t) > 0$	$\frac{\partial \omega(t)}{\partial x} = \frac{d(t)-(1-x_0)dB(t)}{(x+x_0)^2 dB(t)} > 0$
	$dB^U(t) = (1+x)dB(t)$		
	$n = (1+x)dB(t) - d(t)$		
	$\omega(t) = 1 - \frac{d(t)-(1-x_0)dB(t)}{(1+x)dB(t)-(1-x_0)dB(t)}$		
Downward biased	$dB^L(t) = (1-x)dB(t)$	$\frac{\partial n}{\partial x} = 0$	$\frac{\partial \omega(t)}{\partial x} = \frac{d(t)-(1+x_0)dB(t)}{(x+x_0)^2 dB(t)} < 0$
	$dB^U(t) = (1+x_0)dB(t)$		
	$n = (1+x_0)dB(t) - d(t)$		
	$\omega(t) = 1 - \frac{d(t)-(1-x)dB(t)}{(1+x_0)dB(t)-(1-x)dB(t)}$		

F Misestimations in the business-as-usual deforestation path

REDD projects implemented based on misspecified BaU deforestation levels can provide undesired incentives to forest owners and undermine the effectiveness performance of REDD. The two baselines methodologies that could be affected by the errors in the BaU deforestation are the prospective ones, i.e. model-implied or variable corridor. We investigate this hypothesis and solve for the optimal deforestation path when the baseline methodology relies on a misspecified BaU path, such that

$$d^E_{\mathrm{BaU}}(t) = (1+\varepsilon)d_{\mathrm{BaU}}(t) \tag{F.1}$$

where d_{BaU} is the true deforestation path when no REDD programme is in place, and ε is the percentage misestimation of the BaU deforestation rate, with $\varepsilon \in [-0.05, 0.05]$. The corresponding

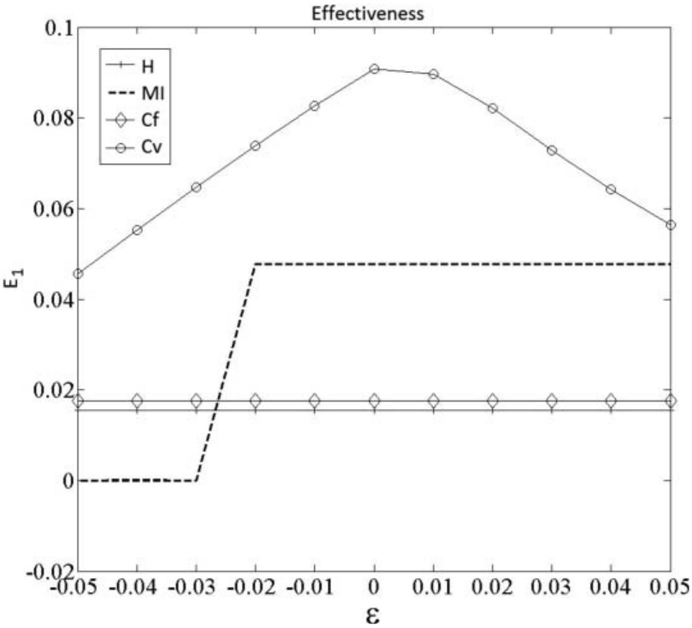

Figure F.1. Realised effectiveness in reducing deforestation when the BaU deforestation is estimated with error ($\varepsilon \in [-0.05, 0.05]$).

REDD revenues ($RR(t)$) take the form

$$RR(t) = \begin{cases} P^R(t)\Big(d^E_{\text{BaU}}(t) - d(t)\Big)^+, & \text{if MI} \\ P^R(t)\Big((1+x)d^E_{\text{BaU}}(t) - d(t)\Big)^+ \left(1 - \dfrac{\Big(d(t) - (1-x)d^E_{\text{BaU}}(t)\Big)^+}{(1+x)d^E_{\text{BaU}}(t) - (1-x)d^E_{\text{BaU}}(t)}\right), & \text{if Cv} \end{cases}$$

where P^R is the price of the carbon permit and x is the corridor wideness, as always.

Figure F.1 captures the effectiveness performance of the four baseline methodologies, when there are estimation errors in the specification of the BaU deforestation. First, for estimation errors that underestimated the BaU deforestation by more than 3%, the landowner will opt out of the REDD project under the model-implied (MI) baseline methodology. Larger estimation errors do not impact their deforestation reduction decisions, and the MI remains more effective than the historical or fixed-corridor approaches.

Second, we find that the variable-corridor methodology is robust if estimation errors stay within [−5%, +5%] from the true BaU deforestation path. Our conclusion that the variable corridor should be the preferred baseline methodology is, therefore, robust.

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